Medical X-ray:
Move Towards Digital and Computerized Systems

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Disclosures

- No financial relationships with any commercial firm.

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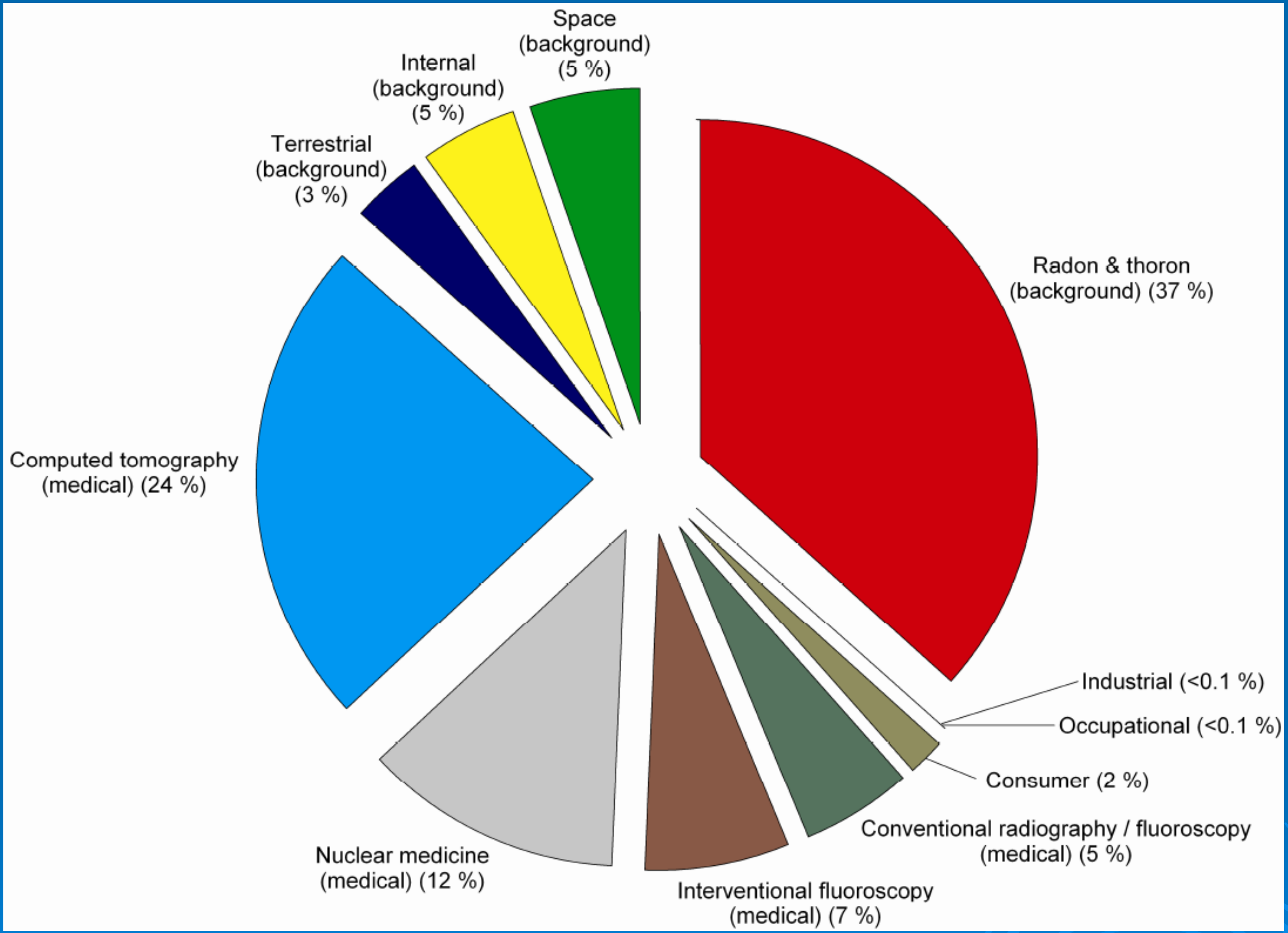
Objectives

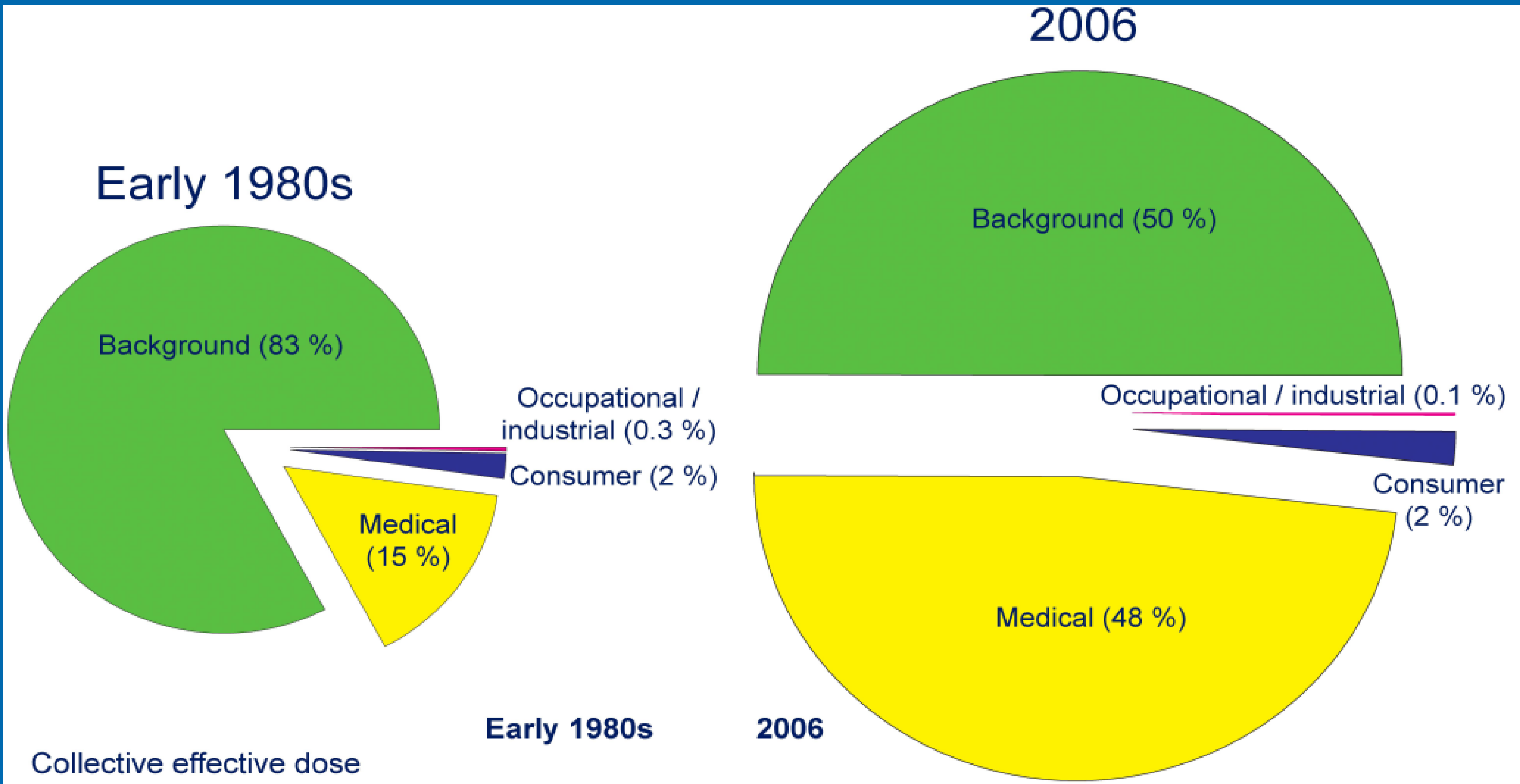
- Identify the technologies and procedures responsible for the increased population dose from medical diagnostic radiation;
- Discuss the impact of moving from film to digital radiography;
- Describe the efforts being taken by the radiology community to reduce patient doses.

Outline

- It's all about radiation dose.
- Radiation interactions.
- Imaging physics.
- Quality control.
- Computed vs. Digital radiography.
- Biological effects
- Principles of protection



From NCRP Report No. 160, “Ionizing Radiation Exposure of the Population of the United States” (2009)



	Early 1980s	2006
Collective effective dose (person-Sv)	835,000	1,870,000
Effective dose per individual in the U.S. population (mSv)	3.6	6.2

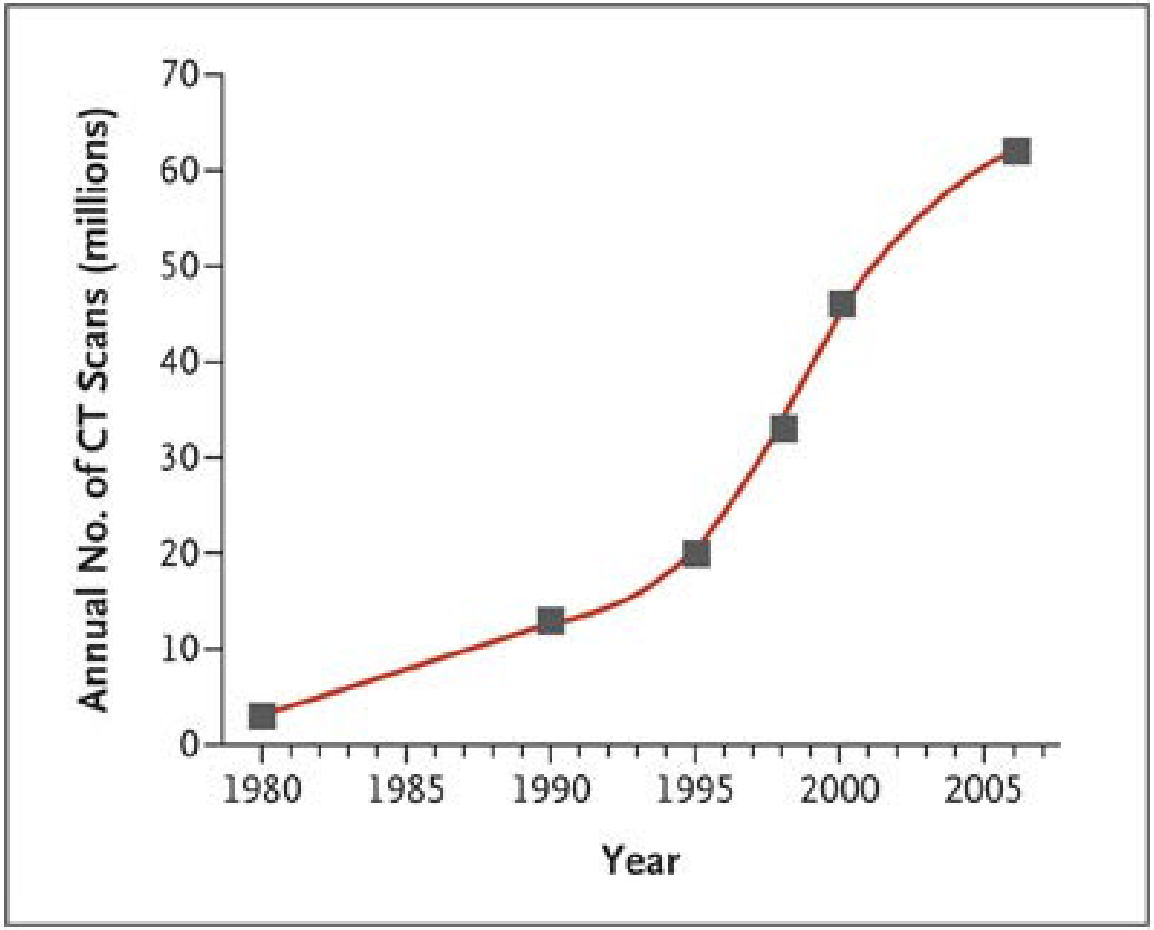
From NCRP Report No. 160, "Ionizing Radiation Exposure of the Population of the United States" (2009)

Concern about Patient Doses

- U.S. population's total exposure to ionizing radiation has nearly doubled over the past two decades.
- Largely attributable to increased exposure from CT, nuclear medicine, and interventional fluoroscopy.
- NCRP estimates that 67 million CT scans, 18 million nuclear medicine procedures, and 17 million interventional fluoroscopy procedures performed in 2006.

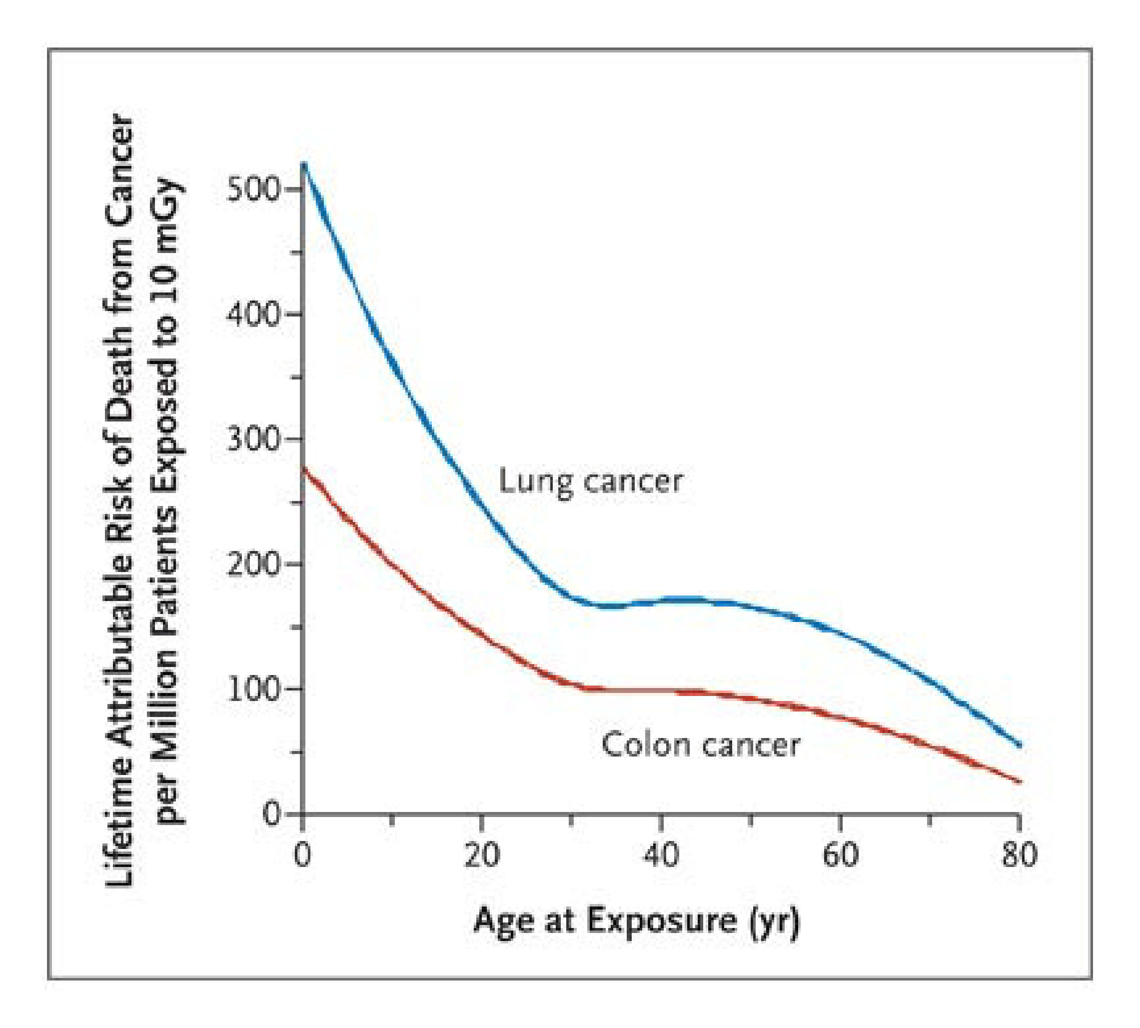
NCRP Report No. 160: 2009

CT Scans Performed Annually in the U.S.



Brenner D, Hall E. N Engl J Med 2007;357:2277-2284

Estimated Lifetime Radiation-Induced Risk of Lung & Colon Cancer Based on Age at Exposure



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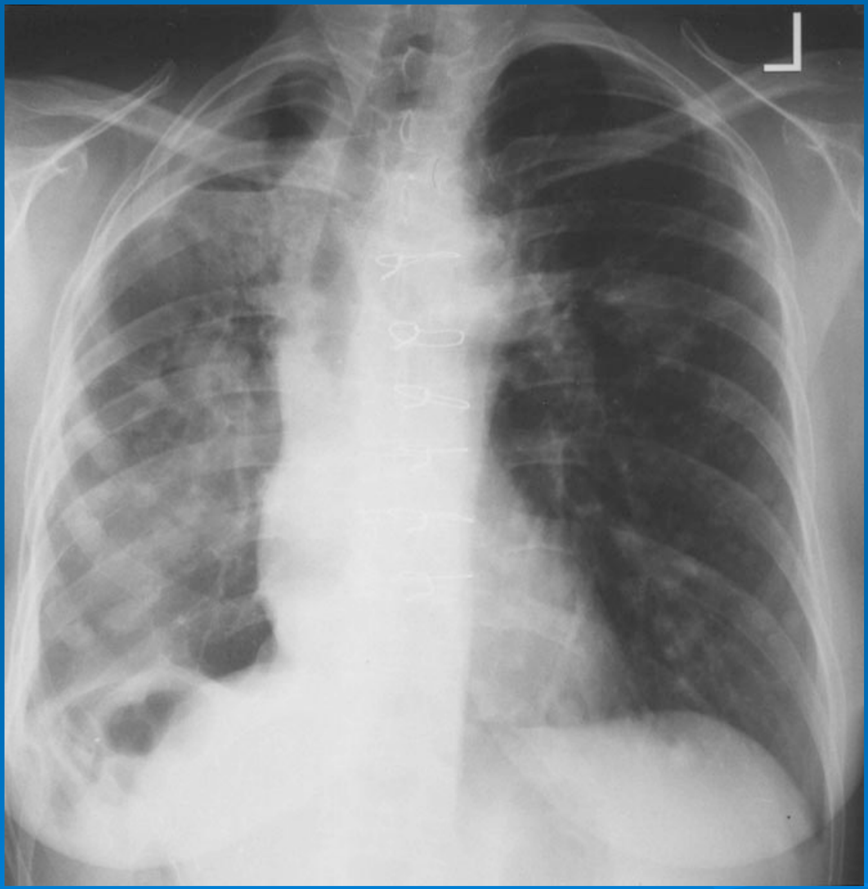
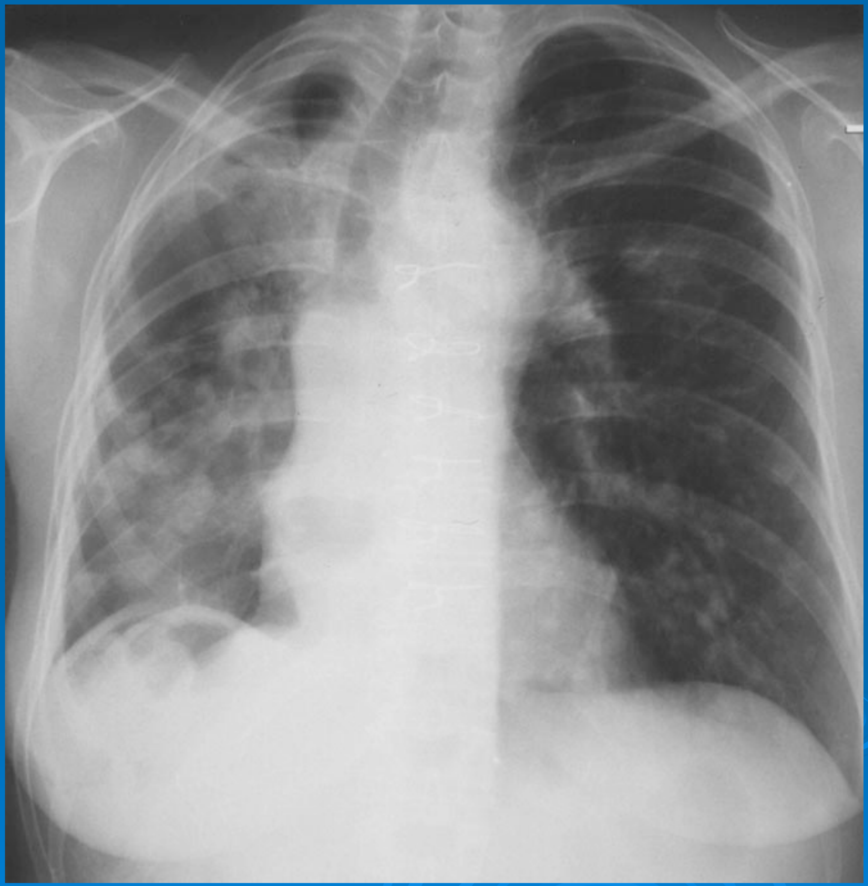
Chest radiograph: 54-year-old woman with lung metastases. Multiple nodules on both lungs, broadening of the mediastinum, and air–fluid level in right upper chest at slightly different levels of inspiration.

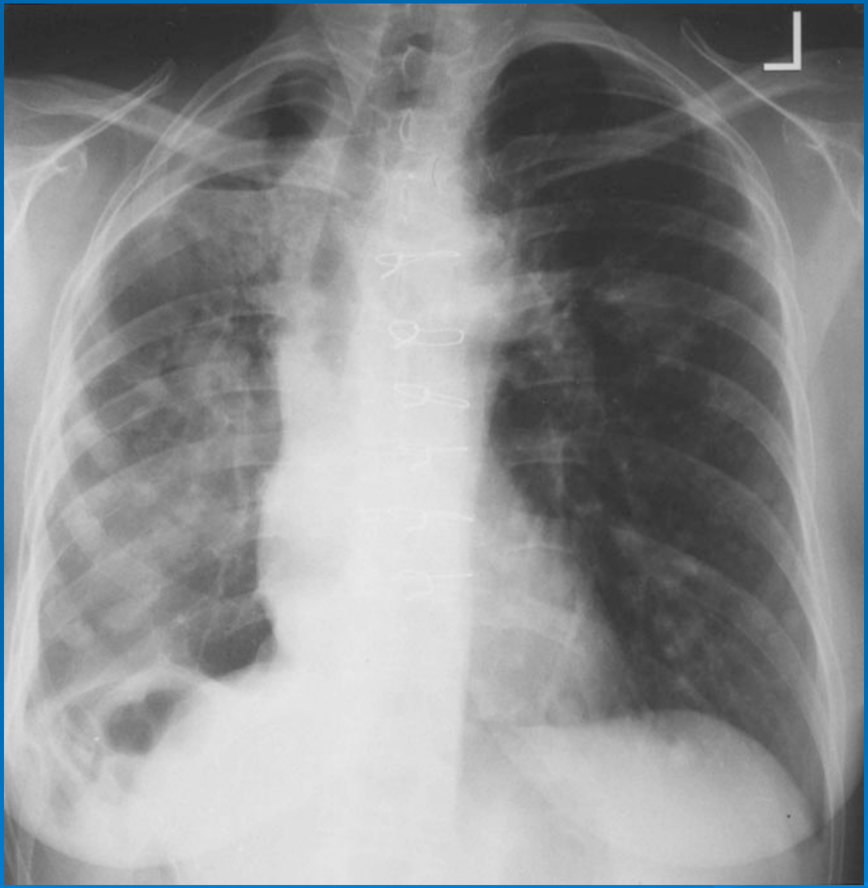




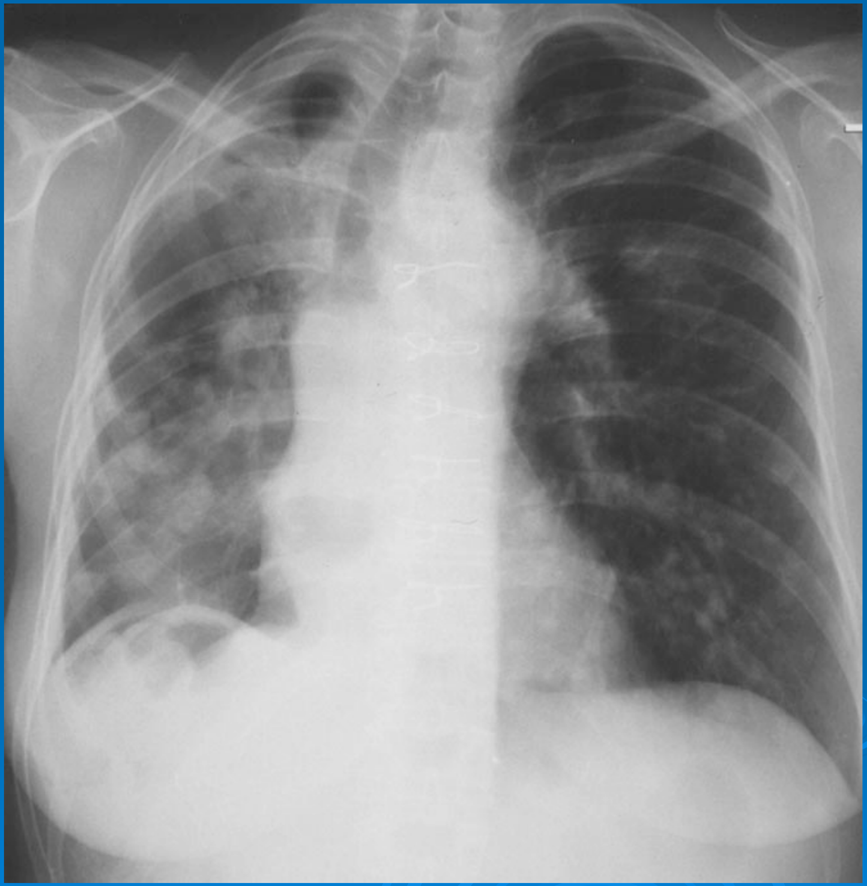
Which image was created with 50% more dose?

Strotzer et al. AJR 178: 169; 2002

Digital chest radiograph



2.5 uGy



1.8 uGy

Strotzer et al. AJR 178: 169; 2002

Digital “lessons.”

- A higher dose does not necessarily create a better image.
- Use least dose necessary to provide clinically relevant information.
- Quality control is just as important with digital as it was with film/screen.

Types of X-Ray Imaging

- Radiography:
  - Two dimensional,
  - Makes up ¾ of procedures but 11% of dose.
- CT
  - 3-dimentional computer generated image,
  - Relatively high dose.
  - Contributes significantly to population dose.
- Fluoroscopy
  - High dose, “live” image.

Average Doses

Radiation Doses from Various Imaging Procedures

Procedure	Adult E (mSv)	# Chest X-Rays
Dental	0.005-0.01	0.25-0.5
Chest	0.02	1
Mammography	0.4	20
CT	2-16	100-800
Fluoroscopy	5-70	250-3500

Mettler, et al. 2008

X-Ray Imaging Physics

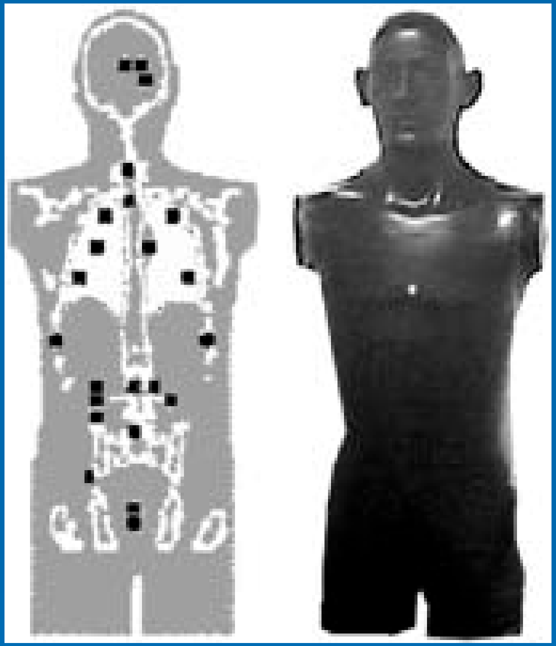
- Advancements: A wide variety of advanced imaging systems with solid state detectors and digital display devices are under development by academia and industry, with a broad range of performance characteristics.

FDA: FY 2010 OSEL Annual Report (http://www.fda.gov)

X-Ray Imaging Physics

- Dose and Image Quality: Much current work is focused on development of high-resolution digital phantoms for use with Monte Carlo simulation software for imaging and dosimetry.

FDA: FY 2010 OSEL Annual Report (http://www.fda.gov)



X-Ray Imaging Physics

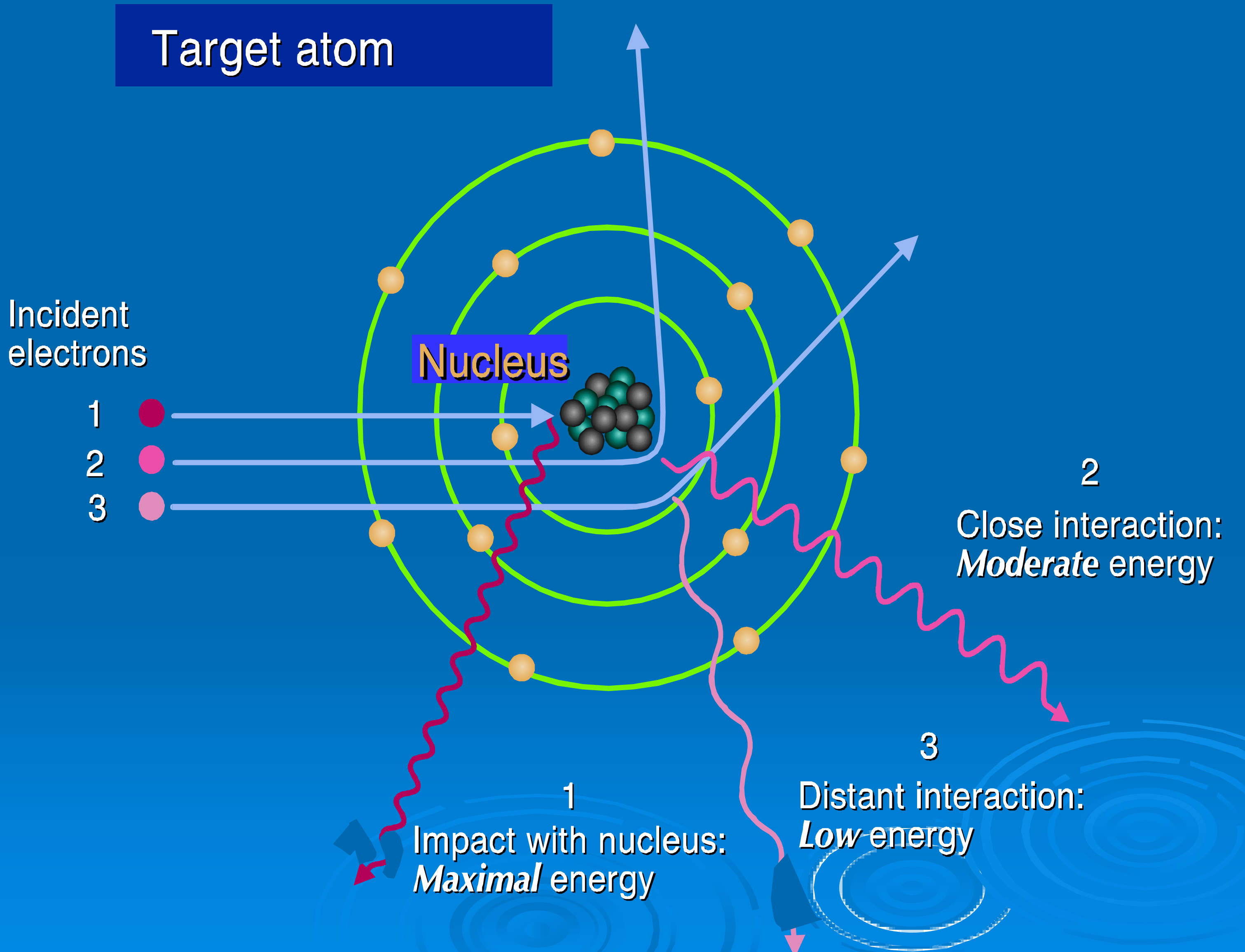
- <u>CT:</u> Much of the work on improving image quality and reducing patient dose is focused on CT.

FDA: FY 2010 OSEL Annual Report (http://www.fda.gov)

Back to the Basics

- The physics of x-rays.
- Interactions ⟶ radiation dose.
- Quality control

Bremsstrahlung X-ray Production



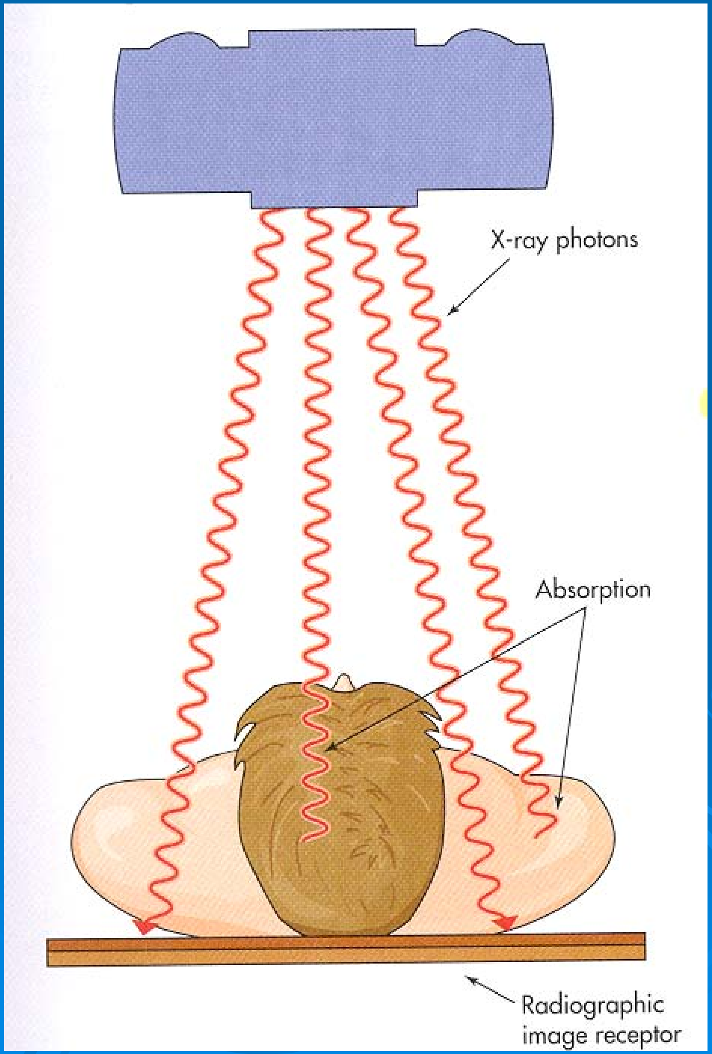
What Are X Rays?

- Some X-ray photons in

the diagnostic range
can penetrate through
the body.

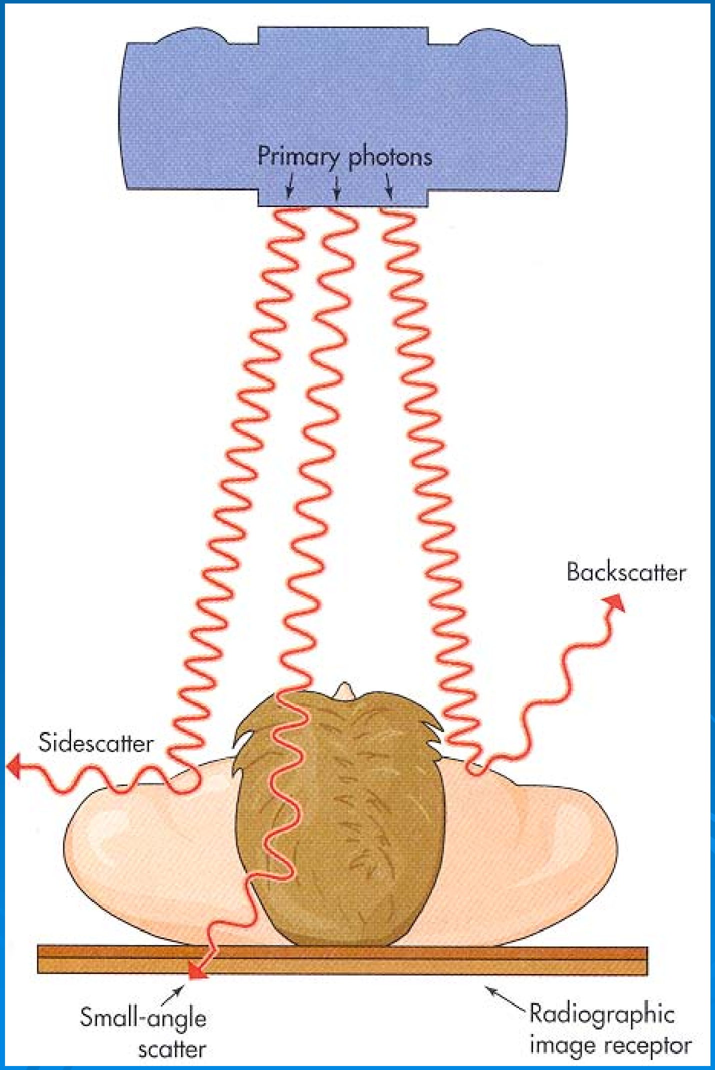
- Photoelectric: Predominates

below ~ 50 keV

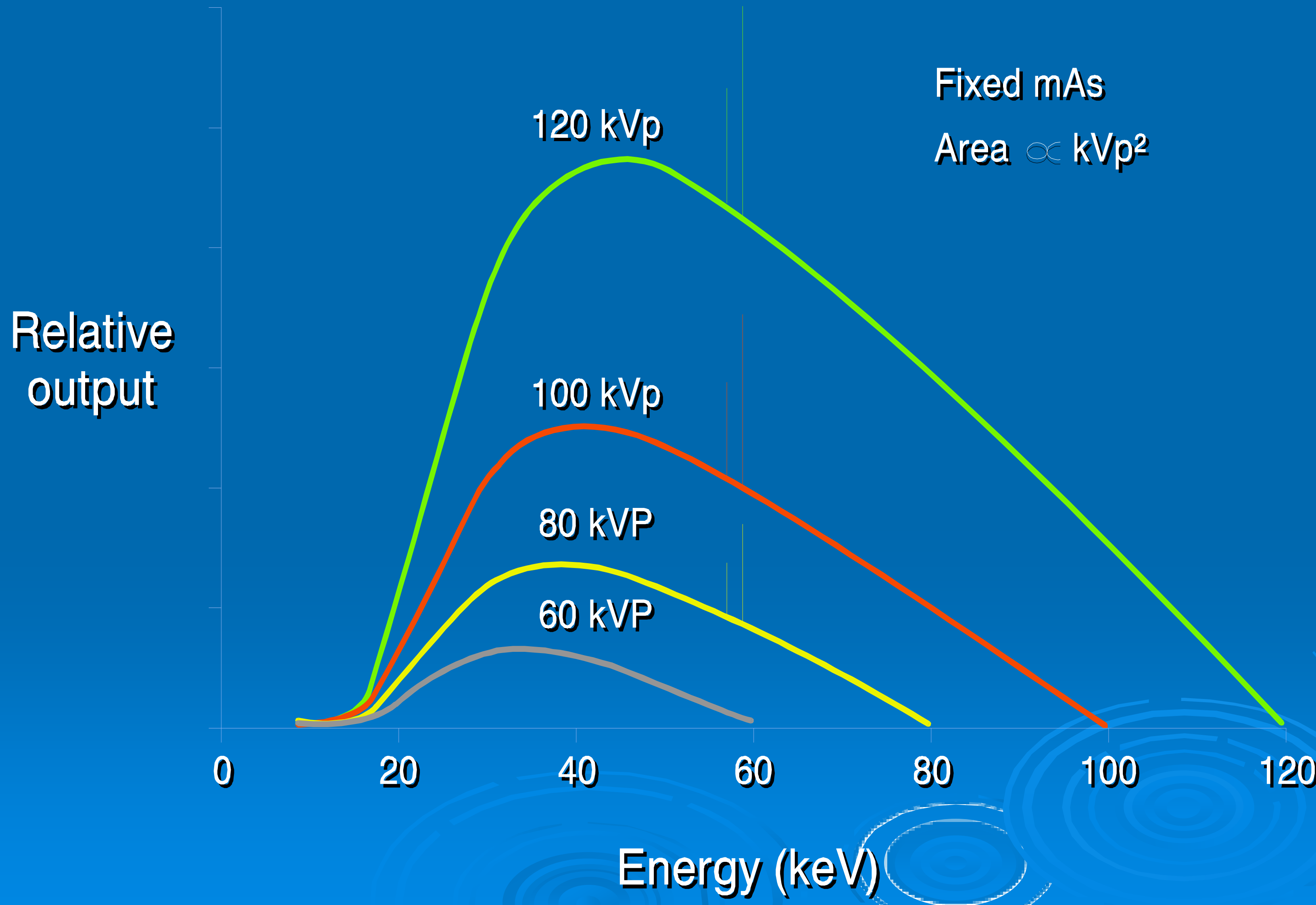


What Are X Rays?

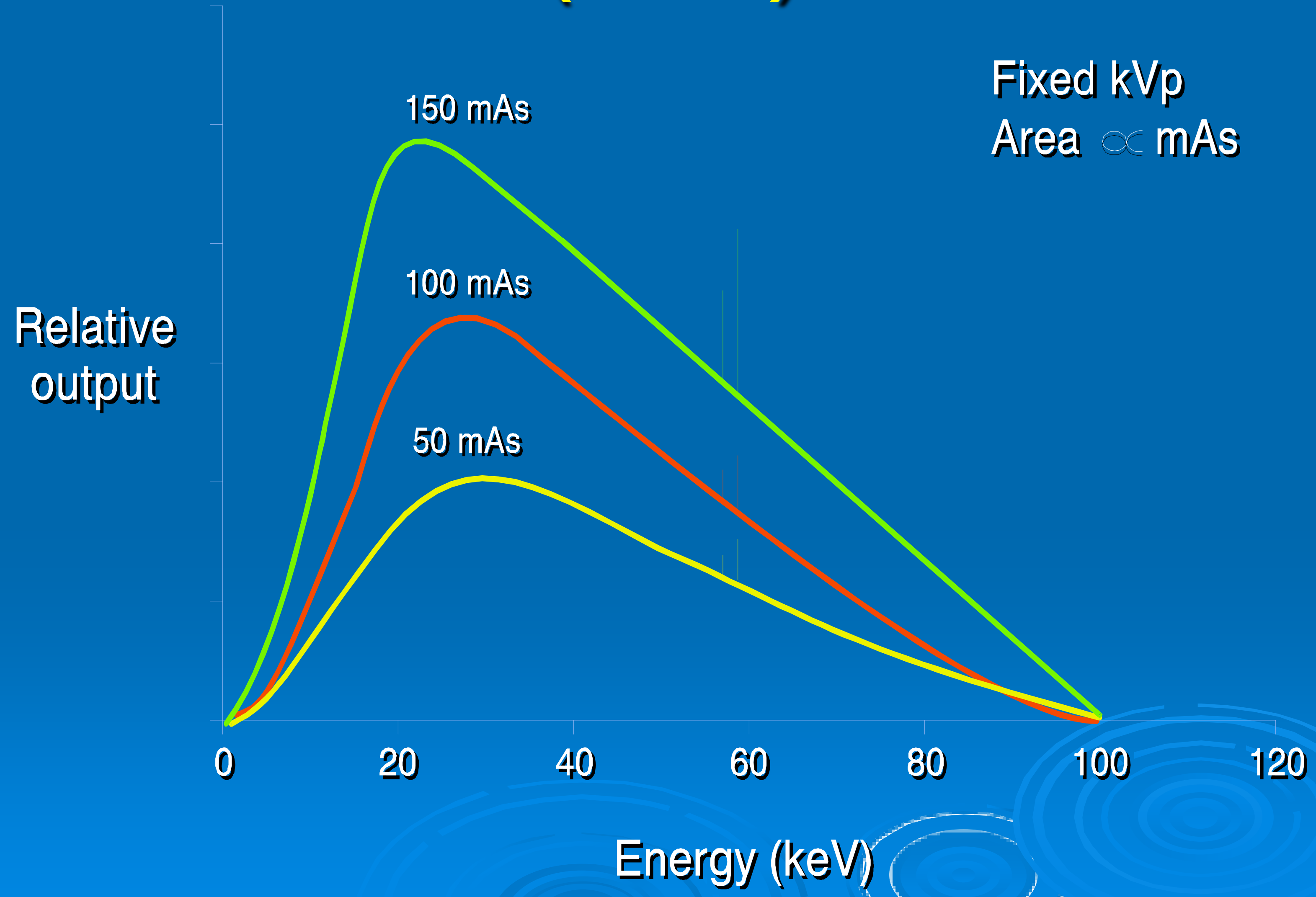
- Some X-ray photons
are scattered by
the patient's body.
- Compton scattering:
  - predominates above ~ 50 keV;
  - does not contribute to image quality;
  - increases radiation dose.



Tube Voltage (kVp)



Tube Current & Exposure Time (mAs)



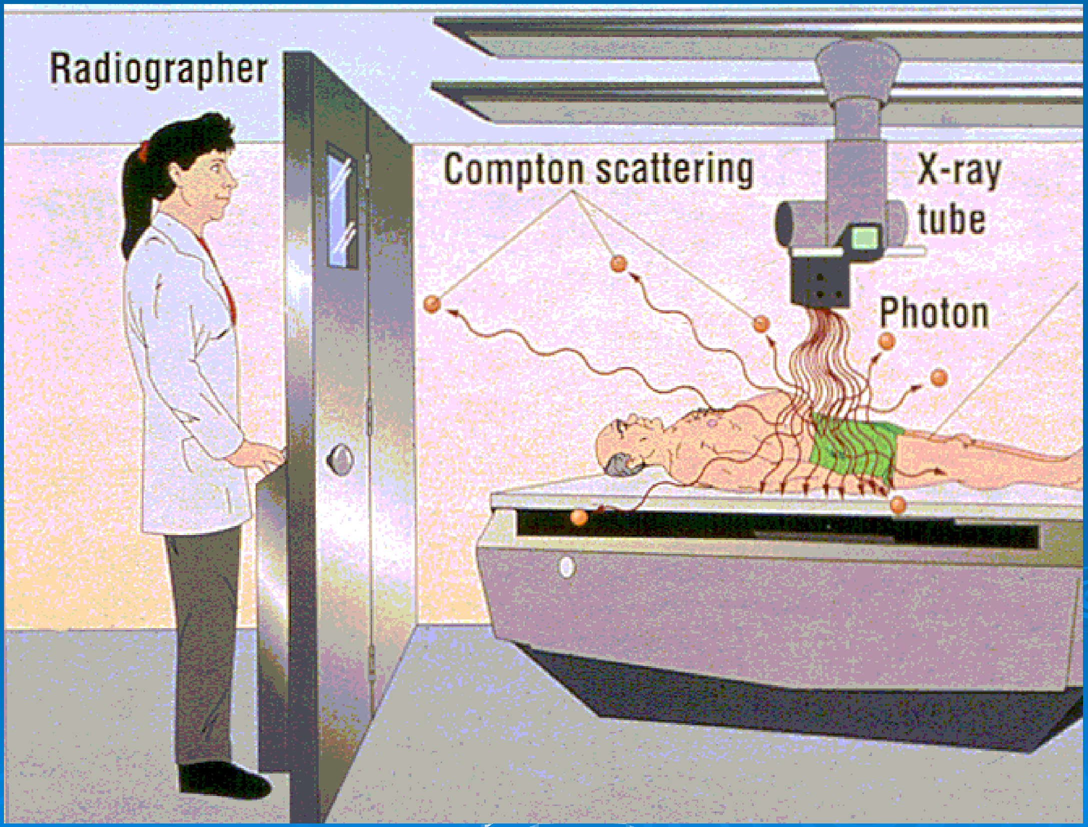
Physics of Radiography

Source:

•Patient

•Table

•X-ray tube



X-Ray Beam Quality (Scatter)

- Image quality
- Patient dose
- Occupational dose


X RAY
ROOM

A Little about Electronic QC

- Bit Depth
- Pixel Pitch
- Matrix Size
- CR vs. DR

Bit Depth

- Defines the maximum number of individual gray values that an image can contain.
  - 12 bits - 4096 levels (0-4095)
  - 10 bits - 1024 levels (0-1023)
  - 8 bits - 256 levels (0 - 255)
  - 6 bits - 64 levels (0 - 63)
  - 4 bits - 16 levels (0 - 15)
  - 2 bits - 4 levels (0 - 3)

Bit Depth

8 Bit - 256 Gray Levels

6 Bit - 64 Gray Levels

Bit Depth

4 Bit - 16 Levels

2 Bit - 4 Levels

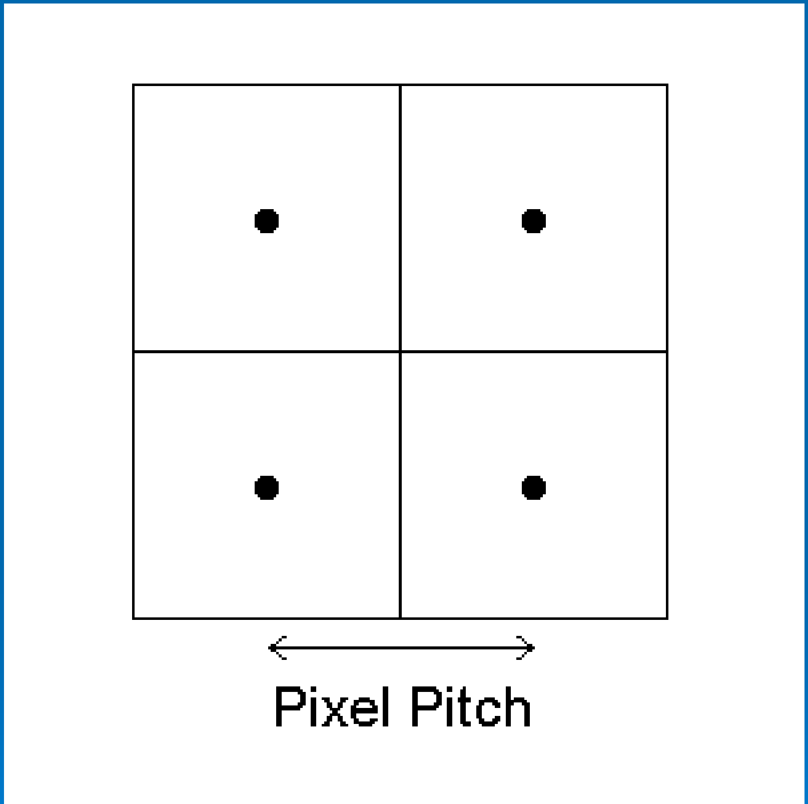
Bit Depth

- Human visual system can perceive about 9 bits.
- Difference between 8 and 10 bits on film printed images is perceivable.
- Difference between 10 and 12 bits is generally not perceivable.
- Modern computer displays are capable of displaying only 8 bits.

Pixel

- Pixel- Individual element of a digital image.
  - Area units (mm^2)
- Pixel pitch- linear distance between adjacent pixels.
  - Length units (mm)

Pixel Pitch



Modality	Pixel Pitch
CR, DR	0.1 - 0.2 mm
CT, MR	0.3 - 1 mm
Digital Mamm	0.025 - 0.1 mm
Nuc Med	3.5 mm

Effects of Pixel Pitch

- Resolution
  - Greater pixel pitch results in lower resolution.
- Noise
  - Greater pixel pitch results in lower noise because more x-ray photons per pixel are used.
- Systems must strike a balance between resolution and noise based on imaging task.

Image Matrix Size

- The number of individual pixel elements contained in the image.
- Usually expressed as the number of pixels in a row and number in a column.
  - Ex. 2048 x 2520 pixels.
- Matrix size = physical distance / pixel pitch
  - 406.4 mm / 0.2 mm = 2032 rows/columns

Pixel Pitch and Matrix Size

0.1 mm, 2032 x 2540

0.2 mm, 1016 x 1270

Pixel Pitch and Matrix Size

0.4 mm, 508 x 635

0.8 mm, 254 x 317

Indirect Digital Radiography

- X-ray signals are converted to visible light, photodiode creates electric charge that becomes a voltage upon readout. Voltage signal converted to digital value.

Direct Digital Radiography

- X-ray energy is converted directly to free electron-hole pairs. Stored capacitance become voltage signal upon readout. Voltage signal is converted to digital value.

Comparison of CR and DR

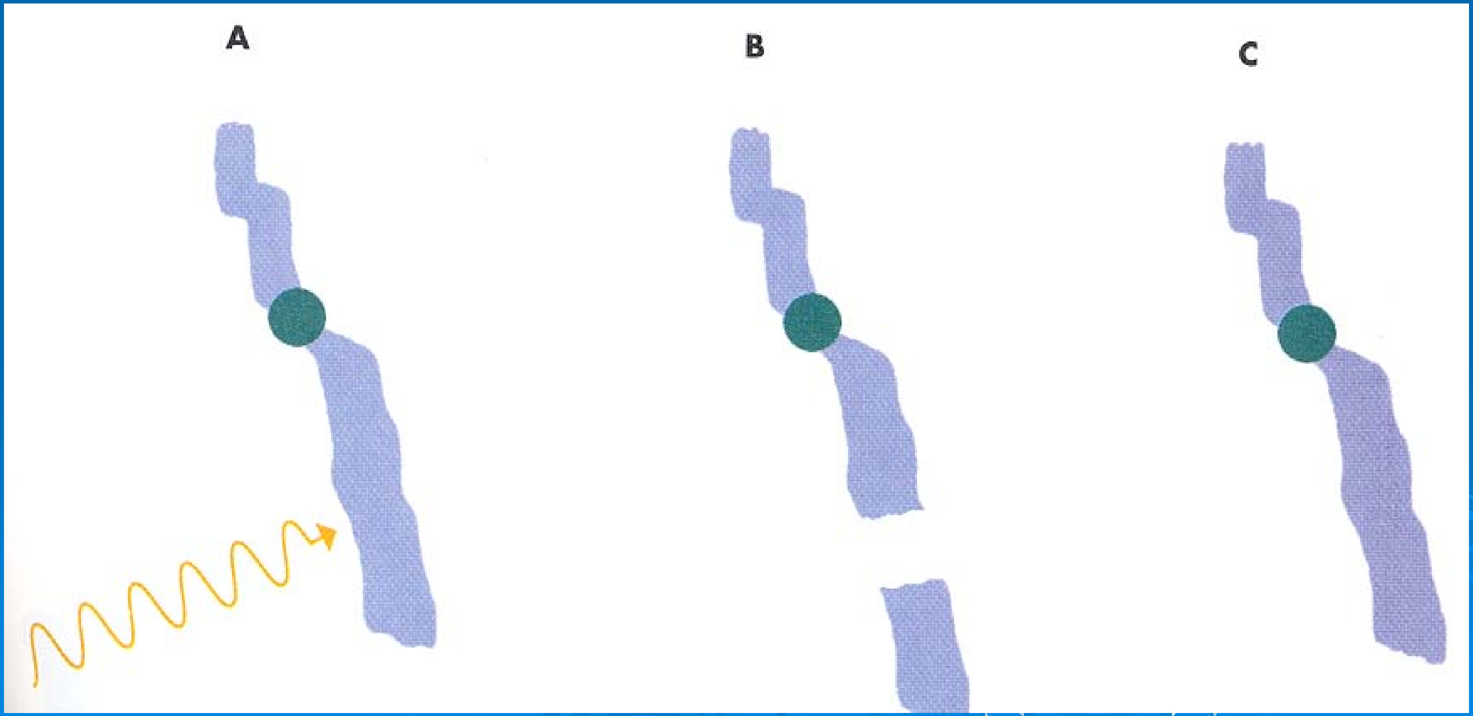
- CR is more versatile
  - Relatively easy transition from film screen
  - range of phosphor plates sizes and pixel sizes
- DR provides superior image quality
  - lower noise result of pixel by pixel correction
  - potentially better resolution

Comparison of CR and DR

- Practical implementation of these modalities is very important
  - Workflow
  - Image processing
  - System compatibility

Can X Rays Cause Harm?

Ionization within the cell nucleus (DNA) may result in permanent damage or cell death



Radiation Measurement Units

- Deep Dose Equivalent (rem): Whole-body dose provided by badge.
- Effective dose (E): average whole body dose weighted by cancer risk to each organ [for those who wear lead apron, E = badge dose (rem) ÷ correction factor for apron (NCRP recommends 21; States may vary]
- Lens dose: badge dose (rem) x correction factor (literature suggests ~ 0.46)

Radiation Measurement Units

Average E from background radiation in U.S. is 100 mrem/year

- Whole-body dose limit is 5 rem/year
- Lens dose limit is 15 rem/year*
- Extremity dose limit is 50 rem/year

*NRC considering alignment with ICRP (10 rem in 5 years with a maximum of 5 in one year)

Typical Badge & Effective Doses for MCR

Average effective whole body annual dose (mrem)

Group	Badge	Effective Dose
X-ray Techs	190	190
CT	1800	320
Vasc Techs	370	70
Urology Techs	50	10
Go Vasc Radiol	1100	200
SMH Vasc Radiol	3200	570
Neuro Radiol	3100	550

Annual Limits:

E	5,000
Lens*	15,000 (2,000)
Skin	50,000
Single Organ	50,000

Bioeffects

Deterministic: threshold, severity increases with dose, e.g. skin erythema

Stochastic: Risk is dose dependent; severity independent of dose, e.g. cancer

Bioeffects

Deterministic: (1 rem = 1000 mrem)

- Cataracts
  - hundreds of rem acute;
  - chronic [New evidence for stochastic effect].
- Skin damage
  - erythema requires > 300 rem to skin; e.g. angioplasty, electrophysiology, ablation.

Bioeffects

Stochastic:

- Cancer
  - most likely requires >5 rem acute, high dose rate or > 10 rem chronic exposure effective dose.
  - background mortality rate ~ 23% (SEER).
  - Based on LNT, risk ~ 0.05% per rem E,
  - thus, risk from E of 200 mrem:

    0.2 rem X 0.05% → ~0.01%

    or increase from 25% to 25.01%

Radiation Protection Philosophy

1. Prevent occurrence of deterministic effects

2. Reduce stochastic effects to a degree that is acceptable relative to benefits to exposed individual and to society

Protection of Personnel

- Reduce patient dose
- Use protective barriers
- Wear protective aprons
- ALARA
- Personnel Monitoring

SHIELDING

Protective Eyewear:

Large diameter lenses are superior to small lenses.

Regular crown glass reduces exposure by about 50%

Leaded glasses up to .75 mm lead equivalence reduce exposure by 98%.

Prudent if whole body badge exceeds 5 rem per year.

Protection of Patients

Justification

- Exam should have clear benefit
- Avoid unnecessary exams
  - require precise medical indication
  - avoid screening exams
- Avoid repeat exams
  - typically 4% in larger hospitals
  - up to 10% in smaller hospitals
  - most due to radiographer error
  - few due to machine problems

Protection of Patients

Optimization

- Use best technique
  - high kVp when possible
  - lowest mAs to give image that provides necessary diagnostic information
- Positioning - avoid intercepting other tissues
- Specific area shielding - e.g. gonad shield
- Image receptor - use fast screen speed

Deterministic Effect: Chronic Radiodermatitis

Cardiac catheterization: patient dose

- Erythema & epilation: 3-8 Gy (300-800 rad)
- Ulceration & necrosis: >15 Gy (> 1500 rad)

(Arch Derm 132: 663 and 695; 1996)

Can X Rays Cause Harm?

High doses of radiation
may cause injury,
e.g. reddening of skin

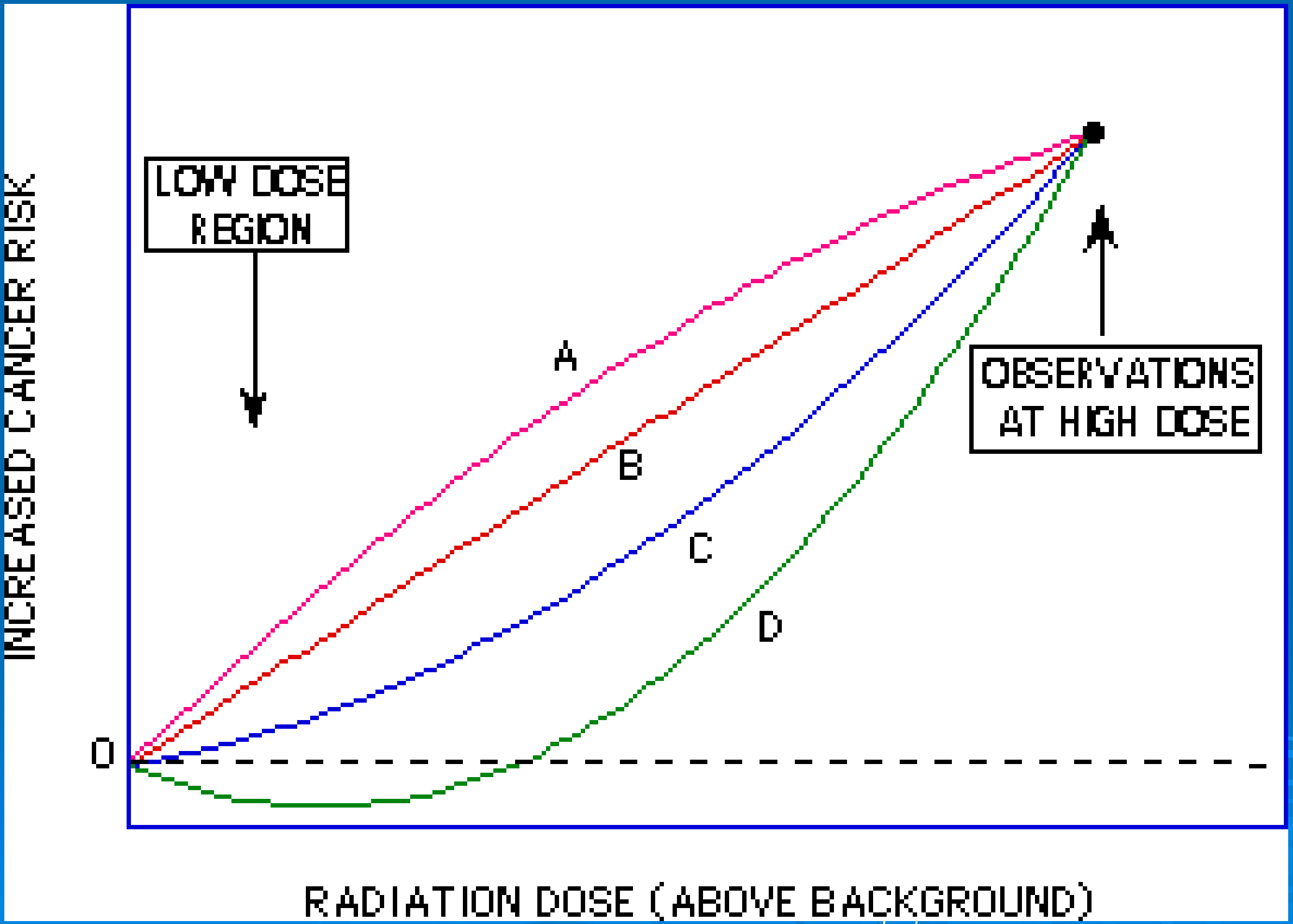
(Arch Derm 132: 663 and 695; 1996)

Average Annual Risk of Death

Cause	**Chance of Death**
All causes	1 in 100
Smoking 1 pack/day	1 in 280
Car accident	1 in 4000
Air travel accident	1 in 100,000
40 mrem radiation*	1 in 50,000

*(typical E from abdominal or lumbar exam)

Stochastic Effect: Radiation Carcinogenesis



Gorski; CDC Blog, 2011

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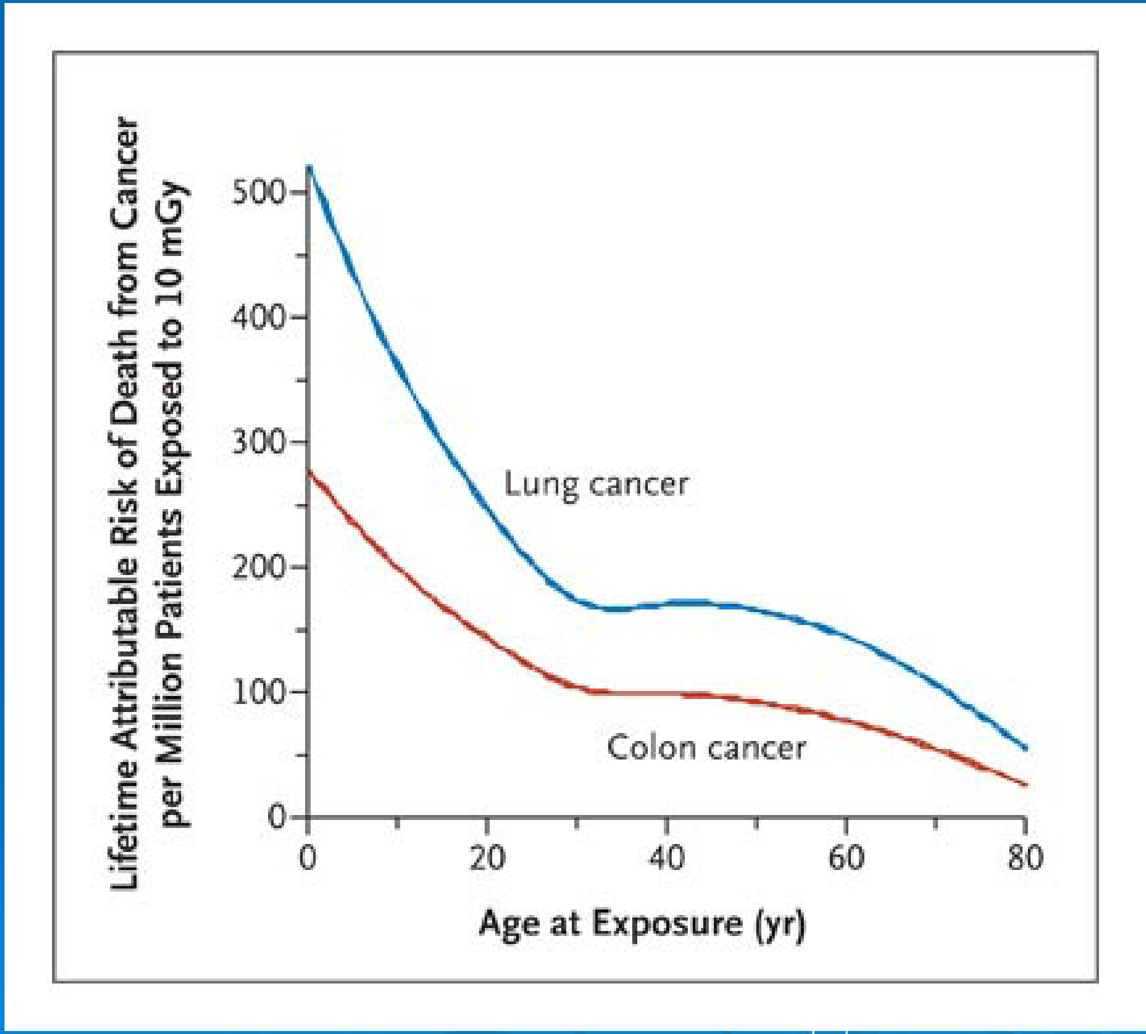

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Pregnancy and Medical Radiation

Probability of bearing healthy children as a function of radiation dose

Dose to conceptus (mGy) above natural background	Probability of no malformation	Probability of no cancer (0-19 years)
0	**97**	**99.7**
1	**97**	**99.7**
5	**97**	**99.7**
10	**97**	**99.6**
50	**97**	**99.4**
100	**97**	**99.1**

Wagner, et al. 1997

Approximate fetal doses from conventional radiography

Examination / Dose	Mean (mGy)	Maximum (mGy)
Abdomen	**1.4**	**4.2**
Chest	**<0.01**	**<0.01**
Intravenous uro-gram; lumbar spine	**1.7**	**10**
Pelvis	**1.1**	**4**
Skull; thoracic spine	**<0.01**	**<0.01**

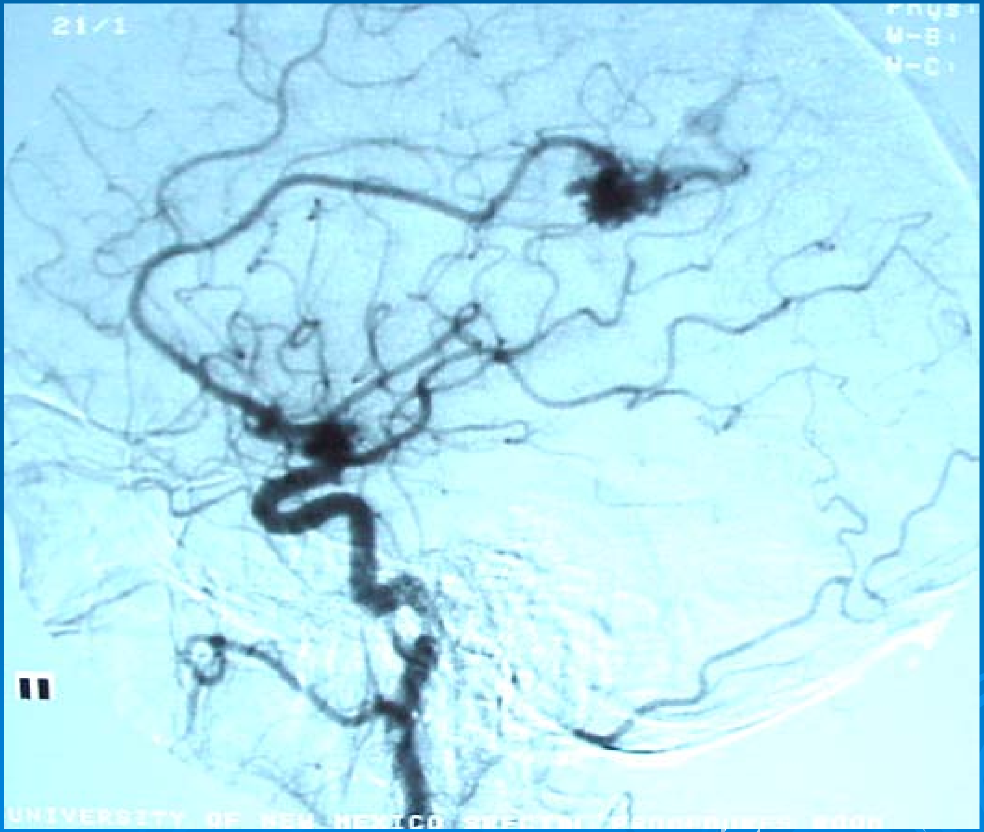
ICRP Publication 84; 2000

Approximate fetal doses from fluoroscopic and computed tomography procedures

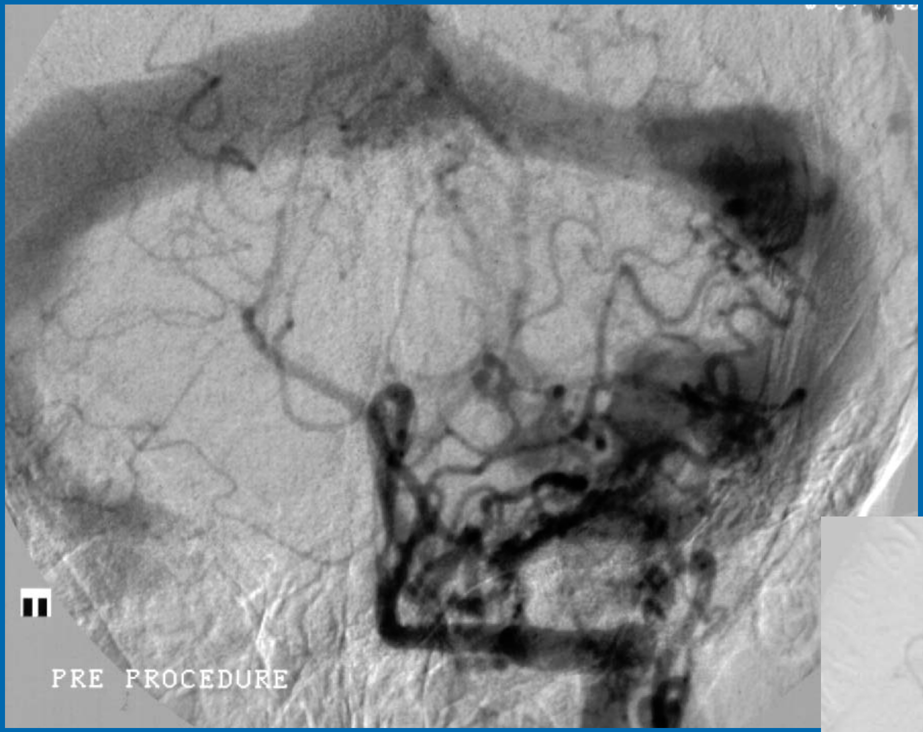
Examination	Mean (mGy)	Maximum (mGy)
Barium meal (UGI)	**1.1**	**5.8**
Barium enema	**6.8**	**24**
Head CT	**<0.005**	**<0.005**
Chest CT	**0.06**	**1.0**
Abdomen CT	**8.0**	**49**
Pelvis CT	**25**	**80**

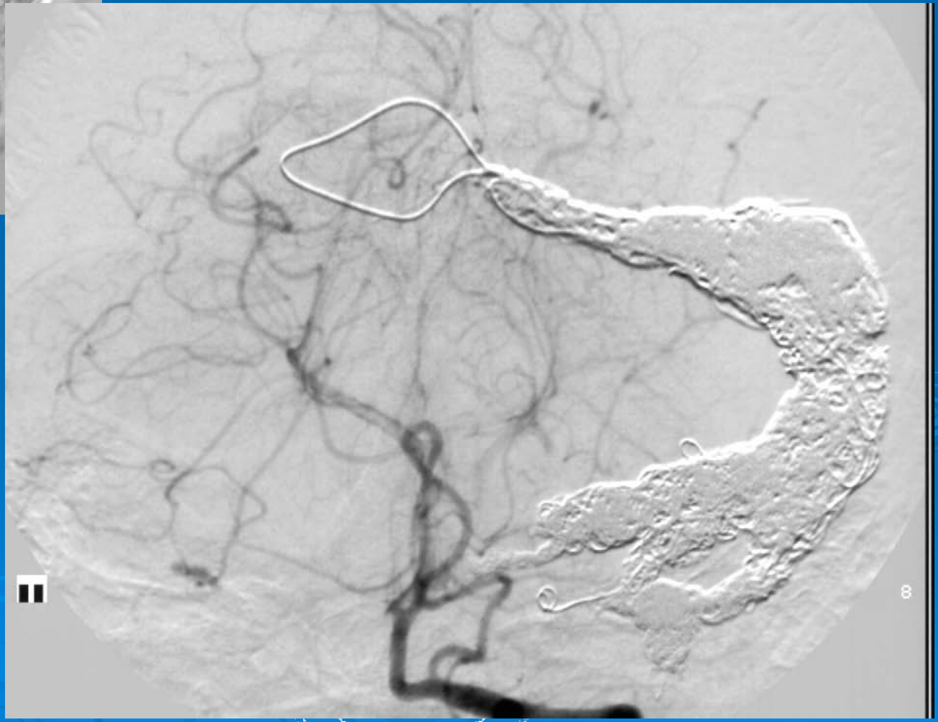
ICRP Publication 84; 2000

Interventional Procedures – Avoiding Radiation Injuries



17 years female - large dural fistula of left lateral sinus





Post embolisation

Images courtesy of Dr JN Higgins

Doses in interventional procedures

Effect	Threshold dose (Gy)	Minutes fluoro at 0.02 Gy/min	Minutes fluoro at 0.2 Gy/min
Transient erythema	**2**	**100**	**10**
Permanent epilation	**7**	**350**	**35**
Dry desquamation	**14**	**700**	**70**
Dermal necrosis	**18**	**900**	**90**
Cataract	**>5**	**>250 to eye**	**>25 to eye**
Skin cancer	**LNT**	**LNT**	**LNT**

ICRP Publication 85; 2000

Interventional procedures

- REMEMBER:
  - Even a straightforward procedure can become high-dose with poor technique
  - However, even with good technique – adverse effects occur

Principles of Protection - Fluoro

- Decrease Exposure Time
  - patient scatter only when fluoro machine is activated ("tap the foot switch")
  - stay out of room
  - minimize fluoro time
  - minimize time near patient during fluoro
    - announce when beam is on
    - step away from patient if not directly involved in procedure

Principles of Protection - Fluoro

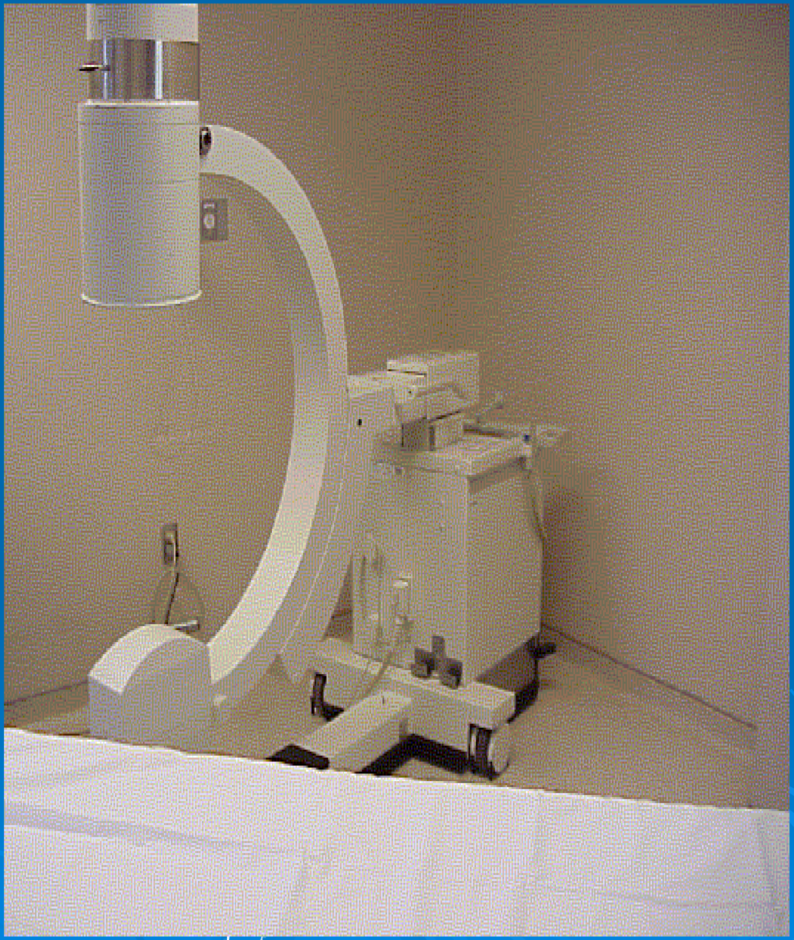
- Impact of Distance

Position	% of pt entrance dose
tableside (1 foot from edge of field)	1%
1 meter	0.1%
2 meters	0.025%

Principles of Protection

- Inverse Square Law and the Patient:

  keep image intensifier as close to patient as possible



Principles of Protection

- Shielding and the patient:

Collimating down protects adjacent tissues and <u>reduces scatter</u>:

- increases image quality
- reduces dose to patient and staff

Controlling dose to patients…

- Keep beam-on time to a minimum
- Dose rates will be greater and dose accumulates faster in larger patients
- Keep tube current as low as possible and tube potential (kVp) as high as possible
- Keep x-ray tube at maximum and the image intensifier at minimum distance from patient

Controlling dose to patients **(cont'd)**

- Always collimate closely to the area of interest
- Prolonged procedures: reduce dose to the irradiated skin e.g. by changing beam angulation
- Minimize: fluoro time, high dose rate time & number of acquisitions
- Don't over-use geometric magnification
- Remove grid for small patients or when image intensifier cannot be placed close to patient

Controlling dose to staff

- REMEMBER:

  Controlling dose to patient will help control dose to staff

Controlling dose to staff

- Wear protective apron & glasses, use shielding, monitor doses – hand dose is often important
- Correct positioning to machine to minimise dose
- If beam horizontal (or near to) operator should stand on image intensifier side, if possible
- If beam vertical (or near to) keep the tube under the patient

Other factors in controlling dose

- Ensure all staff are appropriately trained
- Use dedicated interventional equipment with correct specification
- Ensure comprehensive maintenance and quality assurance programmes are in place
- Obtain advice from a qualified radiation expert

Fluoro Safely

1. Maintain awareness of the room

- Make sure everyone in the procedure room is prepared before starting to fluoro
- Be prepared to stop fluoro if someone enters the room without a lead apron

2. Control the x-ray beam on-time

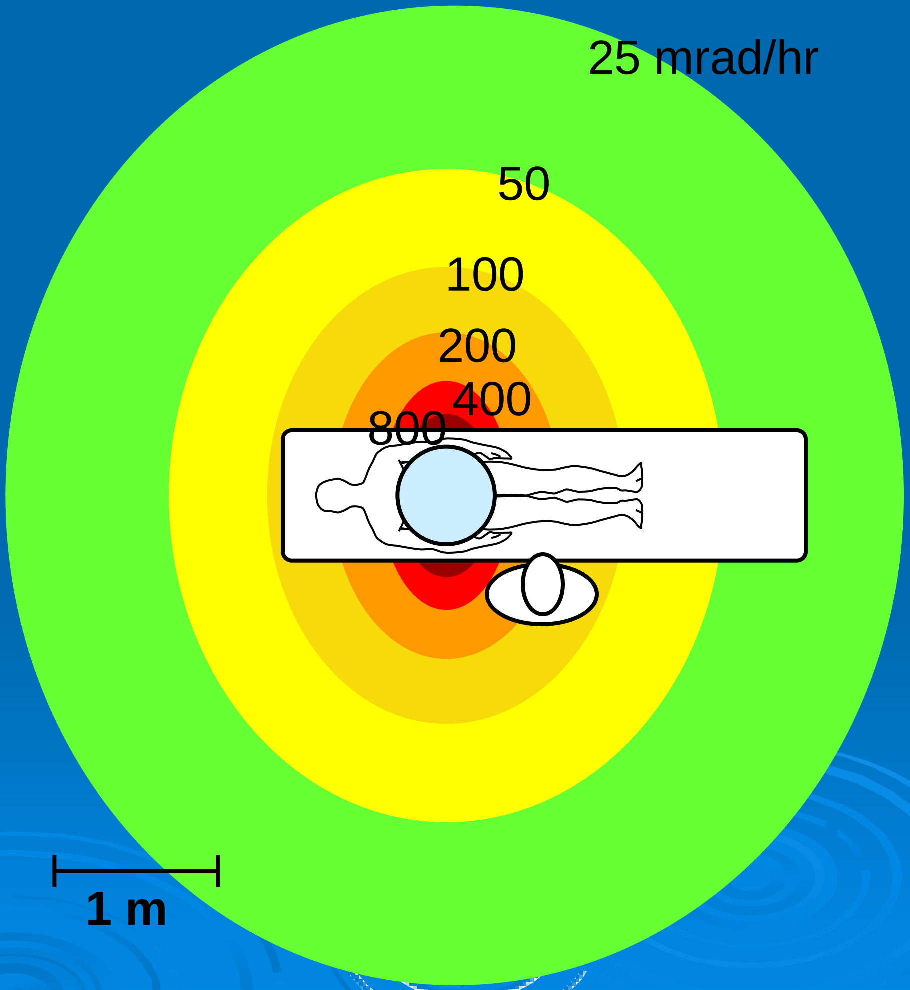
- Use short taps of fluoro instead of continuous operation
- Use the last-image-hold image or acquire a DR image for study or consultation
  - dose for 1 DR = 20 mR which is equivalent to 1 sec of fluoro
- The fluoro unit will sound an alarm after 5 min accumulated on-time
  - Use this help keep track of the fluoro duration

3. Keep hands away from the primary x-ray beam

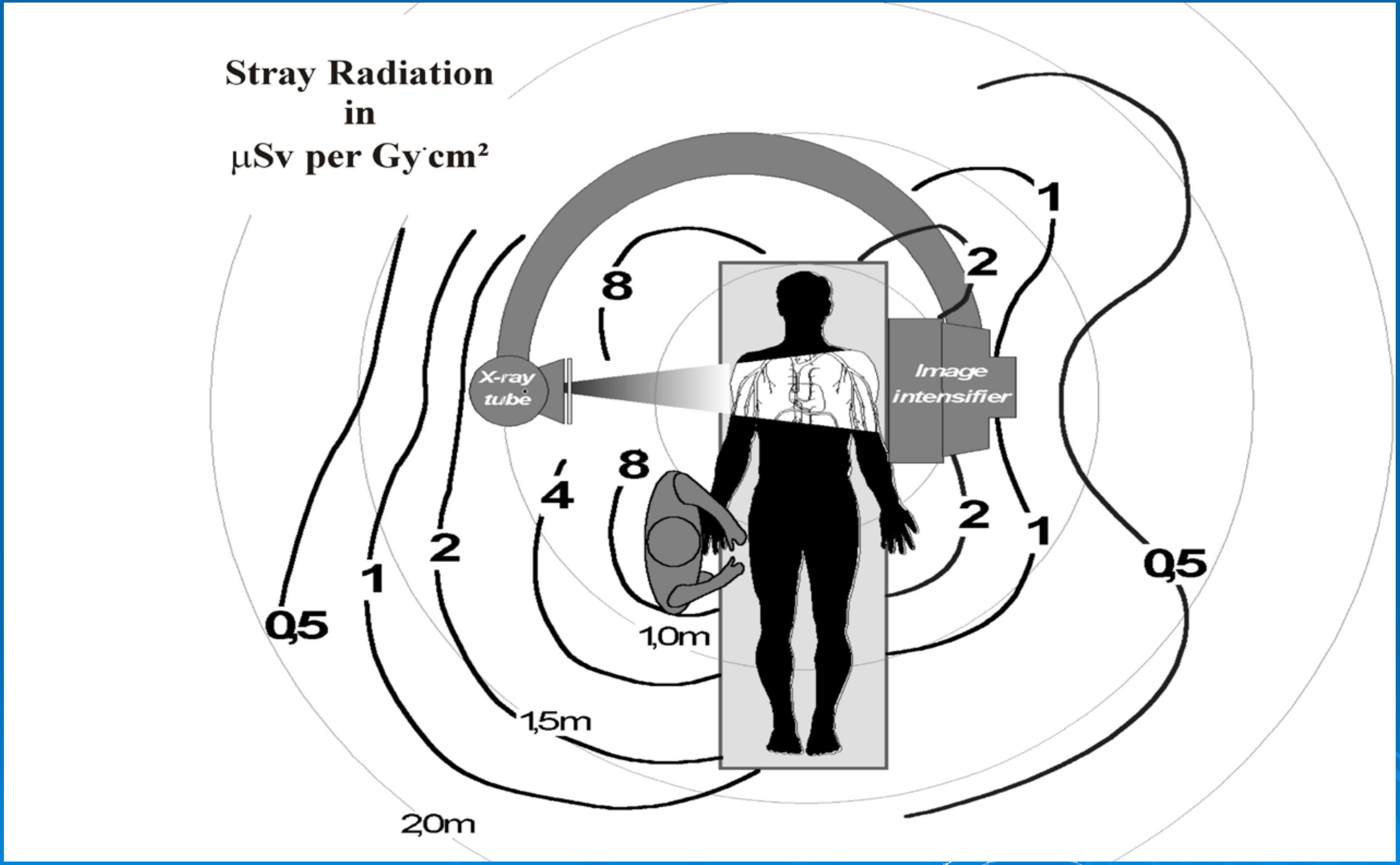
- Use forceps to hold needles
- Inject contrast through tubing extensions

4. Step back from the exposed patient volume when possible

- Radiation levels decrease significantly with distance from the patient



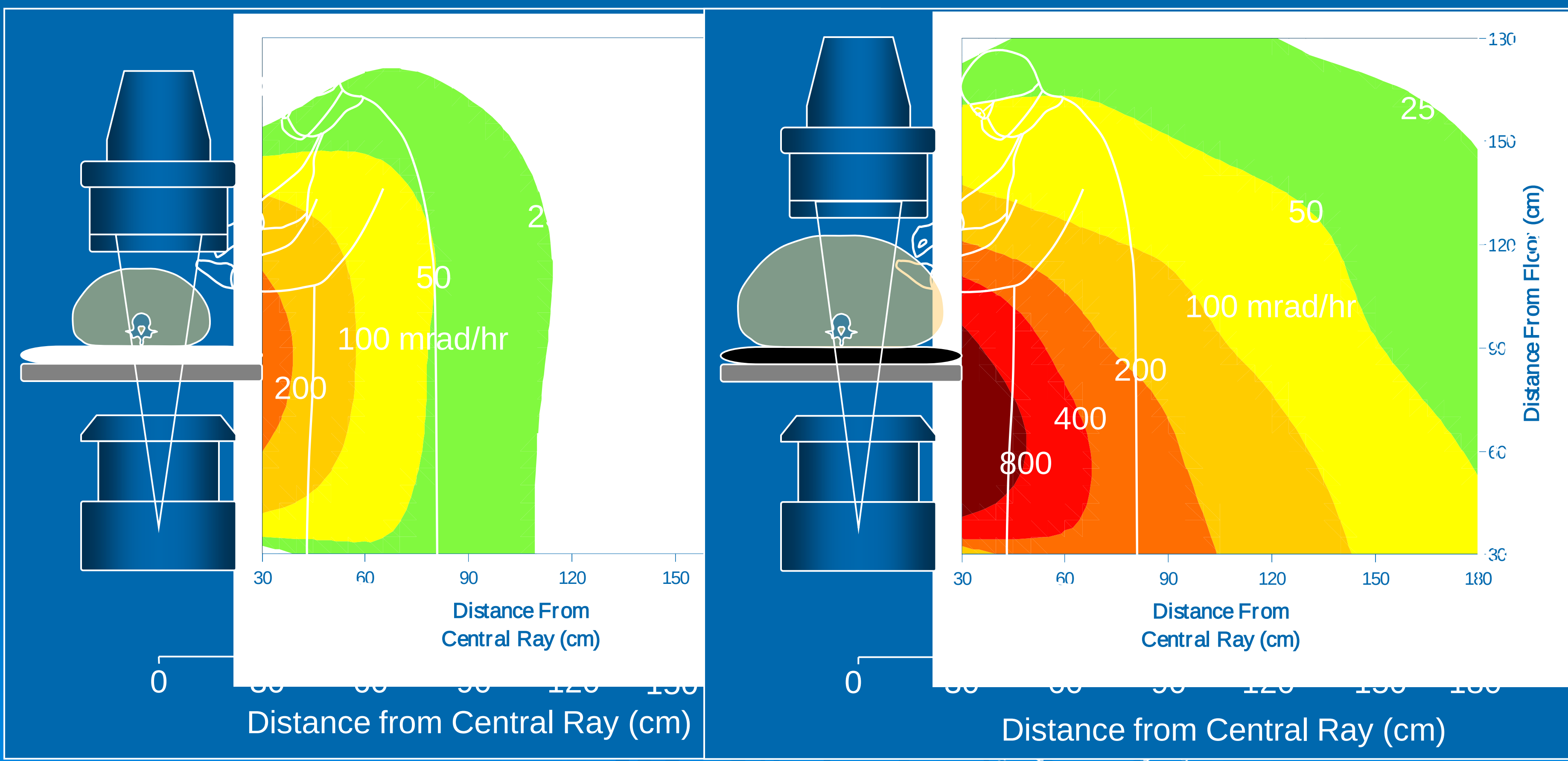
Plan view of an interventional operating x-ray unit with isodose curves



In high dose mode – dose rates will be mSv/hr (same numerical values)

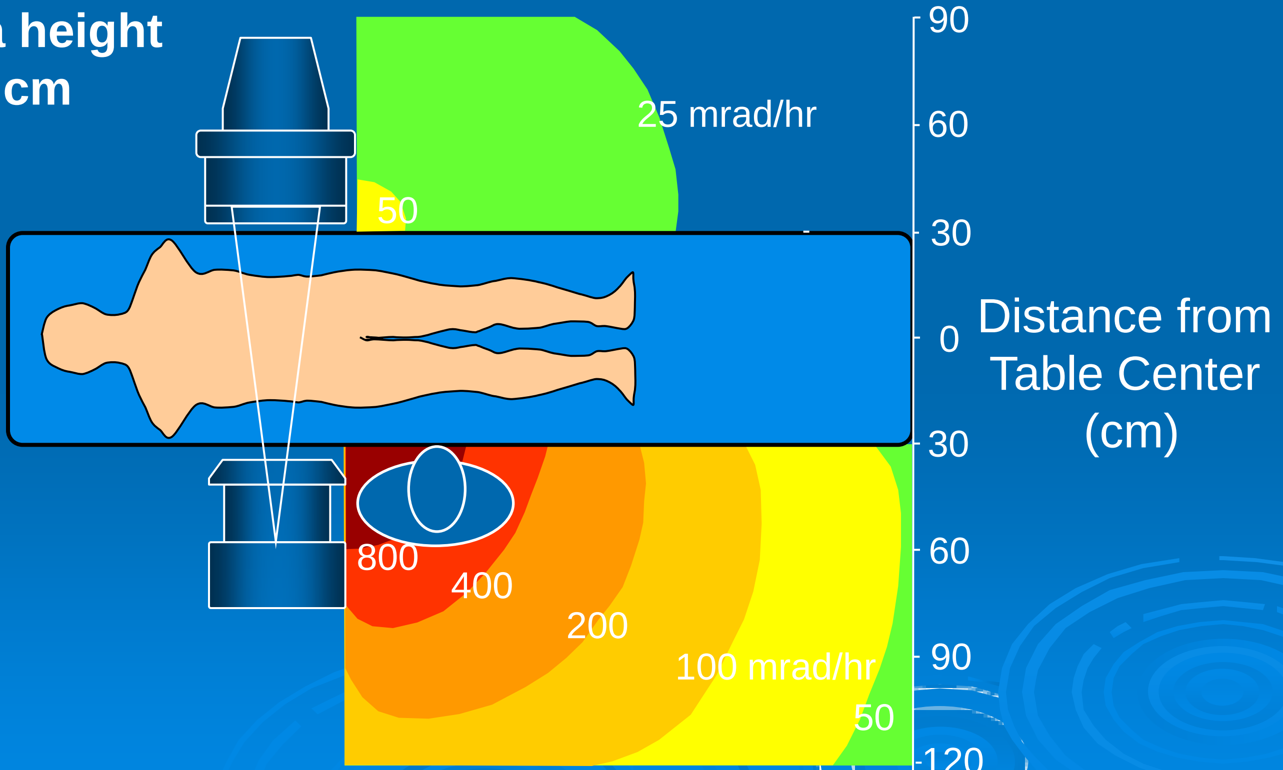
5. Be aware that dose rates are higher for larger patients

Patient dose rate: 1 R/min | **Patient dose rate: 7 R/min**



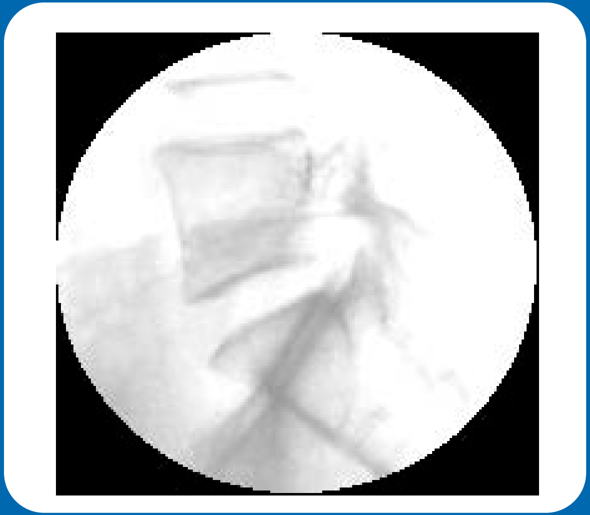
6. Be aware that scatter is higher on the x-ray tube side of the patient

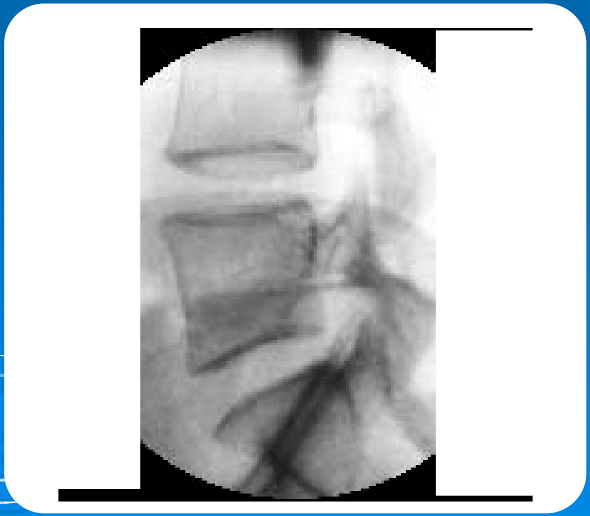
Lateral Projection: Scatter at a height of 100 cm



7. Collimate to the area of interest

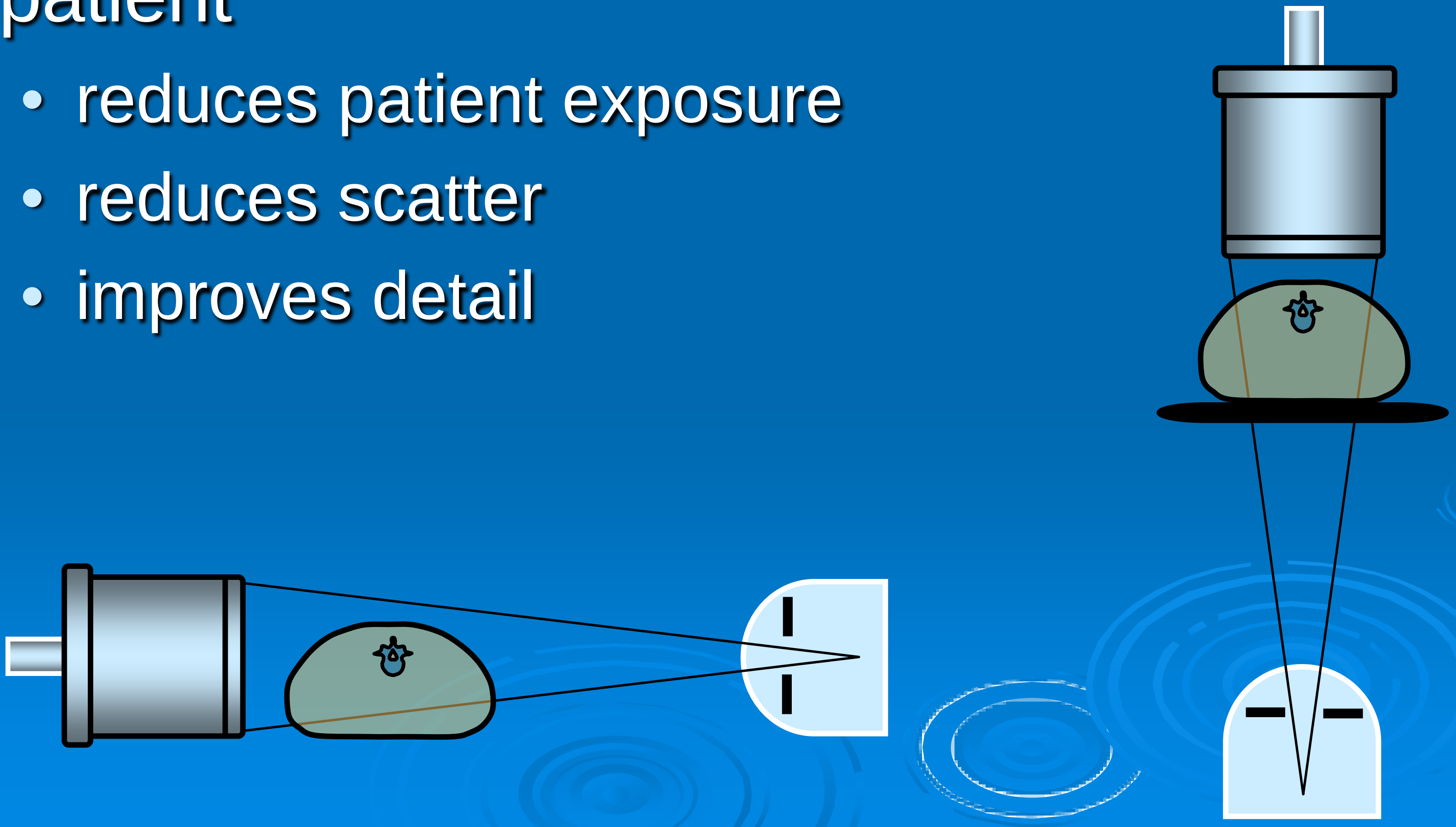
- Improves image quality
  - increases contrast
  - reduces image blooming
- Reduces exposed patient tissue
- Reduces scatter radiation





8. Use optimal geometry

- Position the image intensifier close to the patient
  - reduces patient exposure
  - reduces scatter
  - improves detail



Conclusions

- Greatest contributor to population dose from medical radiation is CT.
- Increasing digital radiography dose does not necessarily improve quality of image.
- Decreasing patient dose also decreases occupational dose.
- Patient dose must be justified and optimized.
- Use time, distance, and shielding to protect staff.

THE END

Questions?