Ionizing Radiation Safety

James F. Kellam
Professor of Orthopaedic Surgery
McGovern Medical School
University of Texas Health Science Center – Houston
Houston, Texas

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Learning outcomes

• Why is this important

• Describe the physical and biological facts of radiation

• Demonstrate an understanding of how to use x-rays during orthopaedic procedures and decrease exposure

• Understand how to protect patients, teams and surgeons from radiation during surgery
Modern Orthopaedics and Ionizing Radiation

Increased use of radiation
  • Diagnostic accuracy
  • Minimally invasive procedures
  • Intramedullary (IM) nailing
  • Surgical efficiency

Always need to justify why you need this radiological investigation

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Why?

• As a surgeon you are responsible for ordering this “test”
• Radiation is dangerous and effects cumulative
• Must be used only as needed
• Limit the potential problems to your patients and you
• Other imaging uses sound waves (ultrasound), magnetic waves (MRI) and not tissue damaging
Physical facts

• Radiation is energy from electromagnetic waves
  • Ionizing radiation penetrates biological tissue

• Frequency: $2.5 \times 10^{17} – 6 \times 10^{19}$ Hz

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Physical Facts: X-ray production

• Heated filament (cathode) produces electrons (tube current in milliamperes \textit{ma})
• Electrons accelerated by accelerating voltage \textit{kVp} to an anode (tungsten)
• Electrons interact with anode to produce x-rays
• \( \uparrow \text{kVp} \) produces more x-rays than \( \uparrow \text{ma} \)

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Physical Facts: Tissue Penetration

Complete Penetration Generates Image
Total Absorption Causes Patient Dose
Scatter Interaction Distorts Image Causes Patient and Staff Dose

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Radiation Exposure: Measurement - Generic

• Roentgen = Quantity of x-rays required to produce an amount of ionization in air at standard temperature and pressure
  • $2.58 \times 10^{-4}$ Coulombs/kilogram (C/kg) for air only

• Gray (Gy) = Energy deposit in a material
  • 1 Gray = 1 Joule/kg = 100 rad (Radiation Absorbed Dose)
  • Reflects physical effect to a material

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Radiation Exposure: Measurement - Biologic

• Sievert = energy deposited in biologic material (absorbed dose x radiation quality factor – x-ray is 1)
  - was Roentgen equivalent in man - rem
  – 1 Sv = 1 Joule/kg = 100 rem = 5.5% chance of cancer

• For human tissue dose multiply Sieverts by a tissue weighting factor to determine the dose in Sieverts – effective dose equivalent (EDE)

• Entrance skin exposure (ESE) amount of radiation delivered to patient skin at point of entry of beam into patient – no adjustment factor
Radiation Exposure: Measurement - Human

• Effective dose equivalent (EDE) calculates the risk of cancer from partial vs total body irradiation in Sieverts
  • < 20 mSv low risk
  • 20 – 50 mSv high risk
  • > 50 mSv very high
## Radiation Exposure: Measurement - Human

<table>
<thead>
<tr>
<th>Radiograph</th>
<th>Effective Dose</th>
<th>Risk Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis (AP)</td>
<td>0.6</td>
<td>1 in 33,300</td>
</tr>
<tr>
<td>Hip</td>
<td>0.7</td>
<td>1 in 28,600</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.01</td>
<td>1 in 2,000,000</td>
</tr>
<tr>
<td>Knee</td>
<td>0.005</td>
<td>1 in 4,000,000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CT Scan</th>
<th>Effective Dose</th>
<th>Risk Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>6.0</td>
<td>1 in 3,300</td>
</tr>
</tbody>
</table>

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Radiation Exposure: Measurement - Human

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Absorbed dose $D_T$</th>
<th>Equivalent dose $H_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI unit or modifier</td>
<td>gray (Gy)</td>
<td>sievert (Sv)</td>
</tr>
<tr>
<td>Derivation</td>
<td>joule/kg</td>
<td>joule/kg</td>
</tr>
<tr>
<td>Meaning</td>
<td>Energy absorbed by irradiated sample of matter - a physical quantity.</td>
<td>Biological effect of radiation type $T$ with weighting factor $W_T$. Multiple radiation types require calculation for each, which are then summated.</td>
</tr>
</tbody>
</table>

**Ionising radiation - Protection Dose quantities in SI units**

**Effective dose $E$**

- Whole body dose to all tissue or
- Tissue weighting factor $W_T$ of each dose:
  - Organ dose to tissue $T_1$ $W_T^{T_1}$
  - Organ dose to tissue $T_2$ $W_T^{T_2}$
  - Organ dose to tissue $T_3$ $W_T^{T_3}$

**Core Curriculum V5**

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Ionizing radiation - Effects

• **Somatic effects**—directly related to dose - determined by dose threshold
  • Early effect: radiation sickness and death
  • Late effect: leukemia, thyroid cancer, radiation cataract
  • Below a certain threshold, no increased risk of radiation-induced problems

• **Stochastic effects**—not determined by dose but by chance
  • Cumulative damage, no threshold
  • Late effect, e.g., thyroid cancer, leukemia

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Ionizing radiation - Effects

• Radiation sickness: 500–1000 mSv
• Radiation from nuclear bomb: 500–1000 mSv
The average person in the United States receives about 360 mrem/yr. = 3.6 mSv

This dose is mostly from natural sources of radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inhaled (radon &amp; its progeny)</td>
<td>2.00</td>
</tr>
<tr>
<td>Other internal (K-40)</td>
<td>0.39</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0.28</td>
</tr>
<tr>
<td>Cosmic</td>
<td>0.27</td>
</tr>
<tr>
<td>Cosmogenic</td>
<td>0.01</td>
</tr>
<tr>
<td>Medical X-ray</td>
<td>0.60</td>
</tr>
<tr>
<td>Total</td>
<td>~ 3.60</td>
</tr>
</tbody>
</table>
Normal radiation exposure
• In USA: natural cosmic radiation is
  • 0.27 mSv/year (27 mRem)

Occupational Risk
Cosmic ray in high-altitude flights: 0.001–0.01 mSv/hour

Pilots have a higher rate Acute Myeloid Leukemia (1.5 X higher)
Dosage with respect to background

- CT angio: 6.7 – 13 mSv
- CT brain: 1.5 mSv
- CT whole body: 9.9 mSv
- Chest x-ray: 0.1 mSv

Normal environmental exposure = 3.6 mSv/year

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Ionizing radiation – Effects: Human Tissue

• Eyes: Most sensitive
  • 150mSv/year (radiation cataract)
  • Somatic effect - cataracts

• Thyroid: 85% of papillary carcinoma are radiation induced
  • Carcinogenic dose of radiation = 50 - 100 mSv
  • Is also a stochastic effect – no threshold

• Hands: greatest exposure risk
  • 500mSv/year
  • Only tendons and bones – more resistant to radiation


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# Ionizing radiation – Effects: Human Tissue

## Common orthopedic procedural dosage

<table>
<thead>
<tr>
<th></th>
<th>K-wire distal radius</th>
<th>Intramedullary nail</th>
<th>External fixator lumbar spine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radiation dose $\mu$Sv (1/1000 mSv)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Eye</strong></td>
<td>1.1 $\mu$Sv</td>
<td>19.0 $\mu$Sv</td>
<td>49.8 $\mu$Sv</td>
</tr>
<tr>
<td><strong>Thyroid</strong></td>
<td>1.1 $\mu$Sv</td>
<td>35.4 $\mu$Sv</td>
<td>55.5 $\mu$Sv</td>
</tr>
<tr>
<td><strong>Hand</strong></td>
<td>3.1 $\mu$Sv</td>
<td>41.7 $\mu$Sv</td>
<td>117.0 $\mu$Sv</td>
</tr>
</tbody>
</table>

Safety regulation limits radiation exposure on professionals to 300–500 mSv/y


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Ionizing radiation – Effects: Human Tissue

Common orthopedic procedural dosage

- Systematic literature review of 34 publications concerning radiation exposure of orthopedic surgeons
- Inconsistent studies
- Highest exposure – spine surgery: 4.8mSv equivalent dose to hand
- IM nailing 0.142 mSv equivalent dose to thyroid
- Reduce exposure by 96.9% and 94.2% with thyroid collar and led apron


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Ionizing radiation – Effects: Human Tissue

Common orthopedic procedural dosage

Radiation exposure with use of the mini-C-arm for routine orthopaedic imaging procedures

Regardless of position, distance, or relative duration of exposure, exposure rates resulting from the use of the mini-c-arm device were one to two orders of magnitude lower than those reported in the literature in association with the use of the large c-arm device.


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Ionizing radiation – Effects: Human Tissue

Common orthopedic procedural dosage

Radiation exposure with use of the mini-C-arm for routine orthopaedic imaging procedures

“After 155 sequential fluoroscopy exposures, totaling 300.2 seconds of imaging time, only the sensor placed in a direct line with the imaging beam recorded a substantial amount of measurable radiation exposure.”

“The surgical team is exposed to minimal radiation during routine use of mini-c-arm fluoroscopy, except when they are in the direct path of the radiation beam.”


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Ionizing radiation – Effects: Human Tissue

Common orthopedic procedural dosage

Hand and body radiation exposure with the use of mini C-arm fluoroscopy

200 consecutive cases (50 cases per surgeon) requiring mini C-arm using badge dosimeters

The total measured radiation exposures for the (1) external whole body exposure dosimeters were 16 mrem (for shallow depth), 7 mrem (for eye depth), and less than 1 mrem (for deep depth); (2) shielded whole body badge dosimeters recorded less than 1 mrem; and (3) ring dosimeters totaled 170 mrem.

The measured whole body and hand radiation exposure received by the hand surgeon from the mini C-arm represents a minimal risk of radiation, based on the current National Council on Radiation Protection and Management standards of annual dose limits (5,000 mrem per year for whole body and 50,000 mrem per year to the extremities).


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Female U.S. surgeons in urology, plastics, and orthopedics were identified using national directories and mailed surveys to collect information on occupational and medical history, including cancer diagnoses. Standardized prevalence ratios (SPRs) and 95% CIs were calculated by dividing the observed number of cancers among female surgeons in each specialty by the expected number, based on the gender-specific, age-specific, and race-specific cancer prevalence statistics in the general U.S.

For female orthopedic surgeons, a **significantly greater than expected prevalence** of any cancer (SPR, 1.85; 95% CI, 1.19–2.76) and breast cancer (SPR, 2.90; 95% CI, 1.66–4.71) were observed.


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Ionizing Radiation Protection

ALARA is the goal

• As low as reasonable achievable

Two areas of concern
A. Diagnostic
B. Procedural
Ionizing Radiation Protection: Diagnostic Usage

• Limit the number of x-rays to the minimum required
  • Evaluate every order – Do I really need?
  • E.g. post op x-rays if have C arm images, what do you really need for fracture follow-up x-rays

• Role of CT scanning
  • Appropriate timing – after reductions
  • Post op – is it justified: reduction, implant position, learning
  • Newer techniques: multi planar fluoroscopy
Ionizing Radiation Protection: Procedural Usage

How to protect the patient, staff and surgeon

• Operator’s position

• X-ray tube position

• Protection measures
Fluoroscope - how it works

- **X-ray Generator**
- **X-ray Tube**
- **Collimator**
- **Filtration**
- **Table**
- **Patient**
- **Image Intensifier**
- **Optical Coupling**
- **Video Camera**
- **Monitor**

- **Gets rid of unwanted x-rays**
- **Radiolucent, carbon fiber**
- **Shutter blades to define beam**
- **Makes x-rays into image**
- **Gets rid of scatter**
- **Takes image from intensifier**
- **Show picture**

**Produces x-rays (ma and kVp)**

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Ionizing Radiation Protection: Procedural Usage

The Importance of Distance and Direction

• Radiation exposure inverse-square law
  • double your distance from x-ray source, you reduce the exposure rate by a factor of four.
• 1 meter away from patient at 90° to the beam = 0.1% of patient’s exposure
• 2 meters – decreased even more by 1/4th

Bushberg – The Essential Physics of Medical Imaging Williams and Wilkins 1994
# Ionizing Radiation Protection: Procedural Usage

## OR Staff Doses

<table>
<thead>
<tr>
<th>Distance</th>
<th>Radiation effect (mrem/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In direct beam</td>
<td>4000 mrem, 40 mSv</td>
</tr>
<tr>
<td>Surgeon 1 ft away</td>
<td>20 mrems to whole body</td>
</tr>
<tr>
<td></td>
<td>29 mrem to hands</td>
</tr>
<tr>
<td>Assistant 2 ft away</td>
<td>6 whole body mrems</td>
</tr>
<tr>
<td></td>
<td>10 mrem hands</td>
</tr>
<tr>
<td>Scrub 3 ft</td>
<td>0</td>
</tr>
<tr>
<td>Anesthesia</td>
<td>0</td>
</tr>
</tbody>
</table>

Mehlman et al J. Ortho Trauma 1997;11: 392-398

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Ionizing Radiation Protection: Procedural Usage

Absorption and scatter

For every 1000 photons

- ~100 - 200 are scattered
- ~ 20 reach the image detector
- Rest are absorbed (= radiation dose) by the patient

Radiation scatter is mainly directed toward the source

The main source of radiation during fluoroscopy is scattered radiation from the patient
Ionizing Radiation Protection: Procedural Usage

X-ray tube position

- The patient is always between the x-ray generator and the operator
- Scatter is directed away from the operator

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Ionizing Radiation Protection: Procedural Usage

X-ray tube position – patient between generator and operator

- Scattered dose is higher at the x-ray tube side

Lateral C arm position

Staff should stay clear of the x-ray tube area

Stand on the intensifier side

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Ionizing Radiation Protection: Procedural Usage

X-ray tube position and operator distance

Double the distance and decrease the dose by 75%

Scatter-dose rate is lower when distance between patient and surgeon increases

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Ionizing Radiation Protection: Procedural Usage

X-ray tube position - height

Scatter dose will **increase** if:
- X-ray tube–skin distance is short
- More magnification
- Occurs with bigger patients

**Reduce scatter**: place patient close to image intensifier and **far from x-ray tube**

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Ionizing Radiation Protection: Procedural Usage

X-ray tube position - height

A. Worst generator close to patient and maximizes scatter

B. Midway position which lessen scatter

C. Best position with generator as far away from patient as possible to decrease scatter as much as possible

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Ionizing Radiation Protection: Procedural Usage

Factors: Patient

As patient size increases skin dose and scattered radiation increases

Protective devices and a safe distance necessary from large size patients
Ionizing Radiation Protection: Procedural Usage

Factors affecting patient doses

A smaller image intensifier diameter can increase patient entrance dose

Magnification increases the dose with locking nails!

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Ionizing Radiation Protection: Procedural Usage

Dose Reduction Aids

• Integrated lasers on both x-ray tube and image intensifier

• Allows easier positioning of beam on patient without using radiation

• Reduce radiation exposure

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Ionizing Radiation Protection: Procedural Usage

Dose Reduction Aids

• Virtual patient anatomy selection ensure correct dose is given to corresponding body area

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Ionizing Radiation Protection: Procedural Usage

Dose Reduction Aids: Acquiring the image

• Avoid foot pedal use – tendency to over radiate

• Technologist takes image shot

• Pulse acquisition - a short pulse of x-rays at the beginning of each frame and manipulated in image intensifier to produce image
Ionizing Radiation Protection: Procedural Usage

Dose Reduction Aids: Acquiring the image

• Selectable dose rate according to patient size
  • Image quality feeds back to x-ray generator to determine the minimal dose for the best image

• “Hold and save” allows last image to be saved to second screen for assessment and planning next step

• Appropriate technique for selected procedure

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Clinical C-arm application

- Landmarks (floor, body)
  - Set up C arm prior to draping for ideal position
  - Mark the floor with tape so technologist knows where machine goes.
- especially important if personnel changes
Practical radiation protection: Personal Devices

Eyeglasses
0.15 mm lead-equivalent goggles provide 70% attenuation of radiographic beam

Thyroid collar
2.5-fold decrease

Apron
AP: 16-fold decrease
lateral: 4-fold decrease

Gloves
60–64% protection at 52–58 KV
Ionizing Radiation Protection: Procedural Usage

Precise Defined Communications

C arm Position

Cant - angle cephalad or caudad

C over - moves in plane of C arm used to get AP lateral and oblique

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Fluoroscopy radiation hazard can be reduced by:

• C-arm orientation
  • Positioning x-ray tube underneath the patient
  • Lateral view: stay away from x-ray tube
  • Keep x-ray tube at maximal distance to the patient
  • Keep image intensifier close to the patient
  • Do not overuse magnification

• Keeping your hands out of the beam!

• ALARA
Take Home Points

• Ionizing radiation is dangerous – patient and surgical team
• Diagnostically - think before order – what do I really need
• Understand and practice the methods of decreasing the does in the operating room