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X-ray irradiator

- Production of x-rays (bremsstrahlung)
- How the x-ray machine works
- Bremsstrahlung X-ray spectrum
- Factors affecting dosimetry
- Case study (John Chute)
Production of x-rays (bremsstrahlung)

- Charged particle (e.g., electron) passing near a nucleus may be deflected by the strong electrical forces exerted on it by the nucleus.
- As the projectile electron passes by the nucleus, it slows down, changes its course, and leaves with reduced kinetic energy. This loss in kinetic energy reappears as an x-ray (called bremsstrahlung x-rays).
How the x-ray machine works

AGFA X-RAD 320
ANATOMY OF ANODE TUBE

- Accelerating Electrons
- Cathode Assembly
- Filament
- Focusing Cup
- Glass Envelope
- Copper Anode Block
- Melting point 1083 deg C
- Tungsten Target

Z=74, High melting point 3380 deg C
Figure II-1. Schematic diagram of an x-ray tube and the basic x-ray tube circuit.
CATHODE ASSEMBLY

- Small filament for high-resolution imaging
- Larger filament for higher intensities (large mA)
TARGET ANGLE AND DIRECTION OF BREMSSTRAHLUNG

- Target angle 10-20 degrees
- Direction of bremsstrahlung radiations (approx. perpendicular to the direction of electrons)

See next slide
RELATIVE INTENSITY OF BREMSSTRAHLUNG

For low energy electrons, radiated predominantly at right angle to the motion of the particles.

The probability of bremsstrahlung production varies with $Z^2$ of the absorbing materials.
FIGURE 11-10 Bremsstrahlung x-ray emission spectrum extends from zero to maximum projectile electron energy, with the highest number of x-rays having approximately one third the maximum energy.
FILTERS, AND BEAM RESTRICTORS

# types of filters

#1: 1.65 mm Aluminum
#4: 0.1 mm Cu + 2.5 mm Al
#8: 0.8 mm Tin + 0.25 mm Cu + 1.5 mm Al
Key factors affecting dosimetry

- X-ray energy (kVp)
- Tube current (mA – milliamperes)
- Beam filtration (filters)
- Distance
- Attenuation in mouse
- Backscatter as a function of field size
Factors affecting dosimetry

- X-ray energy (kVp) – Rule of Thumb (dose increases to kVp\(^2\))

\[
\frac{Dose_2}{Dose_1} \sim \left(\frac{kVp_2}{kVp_1}\right)^2
\]

Dose_2 \sim Dose_1 \cdot \left(\frac{kVp_2}{kVp_1}\right)^2

Example: 120 kVp to 140 kVp

Dose_{140\,kVp} \sim Dose_{120\,kVp} \times \left(\frac{140}{120}\right)^2 = 1.36 \times Dose_{120\,kVp}

i.e., Dose increases by 36%.
Figure II-14. Graphs showing the variation of intensity with energy when electrons with energies of 65, 100, 150 and 200 keV bombard a thick tungsten target as calculated using Equation 2–2. The dotted curves are calculated assuming no filtration, and the heavy curves for a filtration of 1 mm aluminum. The superimposed peaks are the K lines of tungsten.
Factors affecting dosimetry

**Tube current (mA – milliamperes)**

- A change in mA results in a directly proportional change in the amplitude of the x-ray emission spectrum at all energies.
- Example: if you double the mA from 200-mA to 400-mA, the area under the curve (x-ray quantity) doubles.
Factors affecting dosimetry

Effects of beam filtration (filters)

Available filters

- #1: 1.65 mm Aluminum
- #4: 0.1 mm Cu + 2.5 mm Al
- #8: 0.8 mm Tin + 0.25 mm Cu + 1.5 mm Al
Factors affecting dosimetry

Effects of beam filtration (filters)

- The overall result of added filtration is an increase in the effective energy of the x-ray beam with an accompanying reduction in x-ray quantity.
#4 filter being used in Sands Building

#1 filter
#4: 0.1 mm Cu + 2.5 mm Al
#8: 0.8 mm Tin + 0.25 mm Cu +1.5 mm Al
Factors affecting dosimetry

**Effect of distance** (source-to-surface distance, SSD, or target (focal spot)-to surface distance, TSD)

- Inverse-square law (dose decreases inversely to the square of the distance)
- Example: $4\text{ Gy} \times (50\text{ cm}/100\text{ cm})^2 = 4\text{ Gy} \times (1/4) = 1 \text{ Gy}$
Dose depends on the source-to-mouse (target) distance. The closer to the tube, the higher the dose.

Humm... I feel more heat!
Factors affecting dosimetry

- Attenuation in mouse
  - For 135 kVp expect some attenuation in the mouse

- Backscatter as a function of field size

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*Fig. 304.—The variation of percentage backscatter with beam area. Note that rectangular beams have smaller values than circles or squares of the same area.*
CASE STUDY

- John Chute, PI
- Objectives
  - Compare absorbed dose between clinical protocol and direct TLD method
  - Clinical protocol used by Garrette: Parameters: 135kVP, 22mA, @ 100cGy/min, FS (collimated beam): 20 cm x 20 cm
Mouse Anatomy % Bone Marrow

- Skull: 17.6%
- Mandible: 2.0%
- Clavicle and Scapula: 1.0%
- Humerus: 2.4%
- Forearm: 0.7%
- Sternum: 3.8%
- All Ribs: 5.0%
- Femur: 5.8%
- Tibia: 3.0%
- Pelvis: 11.9%
- Spine: 33.7%
- Cervical: 4.2%
- Thoracic: 7%
- Lumbar: 9.9%
- Sacral: 8.1%
- Coccygeal: 2.3%

• *Mus musculus* (Common species of Lab mouse):
  - Avg overall length: 16.9 cm (head to tail)
  - Body length: 6-10 cm (head to base of tail)
  - Hind foot: 1.8 cm
  - Avg weight adult mouse: 17-25 g
  - Average height: 3-5 cm
TISSUE-EQUIVALENT MOUSE PHANTOM

TLD 11, 12

TLD 13, 14

TLD 15, 16

TLD chips (3 mm x 3 mm x 1 mm thick)
## Results: x-ray irradiator

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>CLINICAL SETTING</th>
<th>TLD MEASURED DOSE</th>
<th>% DIFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Head)</td>
<td>500 cGy</td>
<td>406.79 ± 15.61 cGy</td>
<td>-23%</td>
</tr>
<tr>
<td>1 cm deep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (Middle)</td>
<td>500 cGy</td>
<td>427.07 ± 37.23 cGy</td>
<td>-17%</td>
</tr>
<tr>
<td>0.3 cm deep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>500 cGy</td>
<td>441.36 ± 6.12 cGy</td>
<td>-13%</td>
</tr>
<tr>
<td>0.6 cm deep</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Dose rate suspicious
Clinical Setting 500 cGy

X-ray Mouse Dose (cGy)

<table>
<thead>
<tr>
<th>TLD locations</th>
<th>Dose (cGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (1.0 cm)</td>
<td>406.79</td>
</tr>
<tr>
<td>B (0.3 cm)</td>
<td>427.07</td>
</tr>
<tr>
<td>C (0.6 cm)</td>
<td>441.36</td>
</tr>
</tbody>
</table>

Dose (cGy)
New Calibration factors for Garrett geometry

<table>
<thead>
<tr>
<th>Location</th>
<th>Dose Rate (cGy/min)</th>
<th>SD Dose Rate (cGy/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>81.1</td>
<td>3.1</td>
</tr>
<tr>
<td>B</td>
<td>85.4</td>
<td>7.4</td>
</tr>
<tr>
<td>C</td>
<td>88.3</td>
<td>1.2</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>85.0</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Why mice did not die?

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Clinical DR used (100 cGy/min)</th>
<th>New DR (85.0 +/- 2.7 cGy/min)</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>700</td>
<td>595.1 +/- 19.1</td>
<td>-18%</td>
</tr>
</tbody>
</table>

Target 700 cGy was actually 595 +/- 19 cGy.
Desired Dose (cGy) = \( \left( \frac{50 \text{ cm}}{d \text{ cm}} \right)^2 \times \text{DR} \left( \frac{\text{cGy}}{\text{min}} \right) \times T(\text{min}) \)

\[ T(\text{min}) = \frac{\text{Desired Dose (cGy)}}{\left( \frac{50 \text{ cm}}{d \text{ cm}} \right)^2 \times \text{DR} \left( \frac{\text{cGy}}{\text{min}} \right)} \]
GEOMETRY

A: STD=45.5 cm

B: 44.2 cm

STD=50 cm

46.5 cm

1 cm below

0.5 cm deep

3 cm

2 cm

3.5 cm

4.8 cm

STD=45.5 cm
## Results of mice dosimetry

**x-ray irradiator**

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>A: Assume source-to-target distance = 45.5 cm</th>
<th>B: Assume source-to-target distance = 44.2 cm</th>
<th>Dose rate being used clinically by Chute group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose rate</td>
<td>95.0 cGy/min</td>
<td>100.7 cGy/min</td>
<td>100 cGy/min</td>
</tr>
<tr>
<td>Dose for 5 min exposure</td>
<td>475.18 cGy</td>
<td>504 cGy</td>
<td>500 cGy</td>
</tr>
</tbody>
</table>
Discussions

Sources of inaccuracies

- Look-up table (BSF)- probably minor
- Geometry changed since original calibration (major)
- Scatter geometry different in mice in the plastic holder (not uniform water phantom)
Gamma ray irradiator

JL Shepherd
Mark I
Gamma ray irradiator

- Decay scheme (Cs-137)
- Key differences from X-ray
- Case study
- Quality assurance note
Decay scheme (Cs-137)

- Half-life = 30 yrs
- Emits $\beta^-$ particles (electrons)
- Gamma at 662 keV

\[ n \rightarrow p^+ + e^- + \gamma + \text{energy} \]

\[ ^{137}_{55}\text{Cs} \rightarrow ^{137}_{56}\text{Ba} + ^0_{-1}\beta + \bar{\nu} + \gamma \]
Key differences from X-ray irradiator

- **Energy:** Cs-137 662 keV
  - X-ray 135 kVp (ave. energy ~45 keV)
    (average energy ~135 * 1/3= 45 keV)
- **Need for annual decay correction for Cs-137**

\[
e^{-\lambda t} = e^{-\frac{0.693}{30 \text{yr}} \cdot 1 \text{yr}} = 0.977
\]

- The dose rates must be decreased 2.3% per year.
Cs-137 Irradiator Dimension

37 cm high

Cs-137 source will be raised

Turntable
30 cm diam.
Cs-137 Irradiator (Chute)

rotating table

4.8 cm

3”=7.6 cm
Factors affecting dosimetry

- Non-uniform irradiation of mice due to rotating table
- Dose rate point taken at central point and assume same dose distribution (not true)
CASE STUDY

John Chute, PI

Objectives

- Compare absorbed dose between clinical protocol and direct TLD method
- Exposure T = 0.76 min
- Target dose = 500 cGy

CASE STUDY
Geometry issues need to be addressed

Beam angle and TLD chip angle dependency
The beam not always perpendicular to the chips

Goals:
• Understand angle dependency
• Minimize angle effects in dosimetry
8/15/2006 TLD runs: Cs-137 geometry

#1 TLD perpendicular, middle

#2 TLD parallel to beam, middle

#3 TLD parallel to beam, top, same as x-ray

TLD chip 3 x 3 x 1 mm

Beam direction
CLINICAL PROTOCOL DOSE SET TO 500 cGy
Set-up #1

Gold Standard (TLD Cs-137)

A  B  C  average

448.39  430.45  474.52  451.12
Geometry #2, target dose = 500 cGy

Case #2

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>443.52</td>
<td>496.59</td>
<td>457.95</td>
<td>466.02</td>
</tr>
<tr>
<td>500.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TLD parallel to beam, middle
Case #3: x-ray geometry, Target 500 cGy

- TLD parallel to beam, top, same as x-ray #3

- Dose (cGy) graph with values:
  - A: 465.32 ± 500.00
  - B: 429.90 ± 474.10
  - C: 474.10 ± 456.44
  - Average: 462.20 ± 472.30
New calibration factors for Garrett geometry

<table>
<thead>
<tr>
<th>Geometry</th>
<th>DR (cGy/min)</th>
<th>SD (cGy/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (middle, gold standard)</td>
<td>593.6</td>
<td>12.8</td>
</tr>
<tr>
<td>#2 (middle)</td>
<td>613.2</td>
<td>12.6</td>
</tr>
<tr>
<td>#3 (spine curve)</td>
<td>600.6</td>
<td>10.6</td>
</tr>
</tbody>
</table>
Irradiator Dosimetry Quality Assurance Note

- Whenever set-up changes, consult your physicists (Oana and Beverly, Rad Onc or Radccore HP group)
- Geometry specific direct measurements would improve confidence and accuracy
- Calibration factors for specific geometries may be posted in the web-site
- Dose validation is important across the Radccore affiliates
Irradiator safety issues
Irradiator safety issues

- Don’t lose your fingers
- Understand radiation levels in normal operations
Radiation level under normal operations

X-ray beam on

8 $\mu$R/hr @ 1'
9 $\mu$R/hr @ 2'

Assume 10 min exposure @ 1 ft, then

Dose equivalent (Rem) = $8 \frac{\mu R}{hr} \times \frac{R}{10^6 \mu R} \times 10 \text{ min} \times \frac{1 \text{ hr}}{60 \text{ min}} = 1.3 \times 10^{-6}$ R (or Rem)

Recall WB limit = 5 Rem per yr → No radiation risks!
Cs-137 source up

<table>
<thead>
<tr>
<th>location</th>
<th>waist level 3-ft high (1 ft away from wall) uR/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>130</td>
</tr>
<tr>
<td>B</td>
<td>80</td>
</tr>
<tr>
<td>C</td>
<td>300</td>
</tr>
<tr>
<td>D</td>
<td>130</td>
</tr>
</tbody>
</table>

At A, $5 \times 10^{-5}$ Rem for 10 min exposure (Annual limit = 5 Rem)
Safety Summary

- Watch your fingers!
- Under normal operating conditions, no radiation risks exist.