Measurement of Radiation:
Dose – Part 1

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Purpose

• To introduce the concept of absorbed dose and to describe and evaluate methods for measuring dose
• This lecture – dosimetric methods other than ion chamber dosimetry
• Next lecture – ion chamber dosimetry

Exposure vs dose

• Exposure – amount of radiation present in beam
  – Severe limitations as to applicability
  – Biological changes function of radiation absorbed
• Dose – ionizing radiation absorbed per unit mass of absorbing material
Unit of dose

- Unit of dose – Gray (Gy)
  - 1 Gy = 1 J/kg
- Older unit of dose – rad (“radiation absorbed dose”)
  - 1 rad = 100 ergs/g = 0.01 Gy (1 cGy)

Definition of dose

- Let
  - \( E \) = energy deposited in small mass of target material
  - \( m \) = mass of target material
- Then \( D (\text{Gy}) = \frac{E (\text{J})}{m (\text{kg})} \)
- In air, 1 R = \( 86.9 \times 10^{-4} \text{ J/kg} = 0.869 \text{ cGy} \)

Biological response

- Biological response also a function of nature of the radiation
- Define relative biological effectiveness (RBE)
  \( \text{RBE} = \frac{\text{dose of reference radiation to produce given response}}{\text{dose of radiation in question to produce same response}} \)
  \( \text{RBE dose (rem)} = \text{dose (rad)} \times \text{RBE} \)
**Biological response**

- For x-rays and γ rays, usually take RBE=1
  - somewhat higher for neutrons, π mesons, etc
- RBE a function of radiation, also of biological response

**Measurement of dose**

- Fundamental measurement from definition: measure amount of energy absorbed in target material
- Easier than to measure ionization
- Must convert energy of ionizing radiation into some other form of energy that is easier to measure

**Calorimetry**

- Radiation energy converted into heat energy
  - Heat causes temperature rise
  - Temperature rise can be measured
  - Energy absorbed by target material – E
  - Temperature rise – ΔT
Calorimetry

- Radiation energy converted into heat energy
  - Then \( E = C \Delta T \)
  - \( C \) – specific heat – property of target material

- Radiation dose \( D = C \Delta T/m \)

Calorimetry

- Example: The specific heat of graphite is 170 cal/kg°C. What is the absorbed dose in a graphite block of a calorimeter if the temperature of the block increases by 0.2 Celsius degrees?

\[
D = \frac{4.186 \times 10^2 \text{cal/kg°C}(0.2 \text{ °C})}{10^{-2}}
\]

\[
= 4.186 \times 10^2 \times 170 \times 0.2
\]

\[
= 14,200 \text{ cGy}
\]
**Calorimetry**

- Absolute measurement of dose
  - Does not need calibration
  - Can be used as dose standard

**Disadvantages:**
- $\Delta T$ very small
  - Require sensitive temperature measuring device
- Require heavily insulated target material
  - Only temperature rise due to radiation and not due to thermal conduction with surroundings
- Calorimetry not generally used as clinical technique

**Film dosimetry**

- Absorption of radiation causes chemical change in silver halide crystals giving rise to deposition of metallic silver
- Amount of deposition (film blackening) related to amount of radiation absorbed
Film dosimetry

- Transmission of light:
  \[ T = \frac{I}{I_0} \]
- Optical density:
  \[ D = \log\left(\frac{1}{T}\right) \]

Generally measure \( D \) vs \( \log E \)

- \( E \): exposure
- Procedure is to measure optical density and refer to calibration curve
- Significant advantage of film dosimetry – very good spatial resolution

Disadvantages:
- Requires calibration - HD curve
- Limited range – latitude
  HD curve exhibits toe and shoulder
- Particularly sensitive to low-energy photons
  High absorption for photoelectric effect due to high \( Z \) of silver enhances contribution from low energy scattered photons
  Newer films exhibit less sensitivity to low-energy photons
**Film dosimetry**

- Excellent technique for measuring dose distributions for electron beams
  - No low energy photons
  - Electron beam distributions have sharp gradients
    - Take advantage of spatial resolution of film
  - Get hard copy of dose record

- Also useful for measuring isodose curves for megavoltage photon beams
  - Accuracy of ~3%

**Radiochromic film**

- Thin layer of radiosensitive dye bonded to Mylar base
- Measure degree of coloring with spectrophotometer or laser scanner
- Almost tissue equivalent (effective Z of 6.0 – 6.5)
- Must be calibrated prior to use
Chemical dosimetry

- Radiation-induced chemical reactions
  - Number of molecules affected is function of energy absorbed
  - Define G-value: \( G \) = number of molecules affected per 100 eV absorbed

Chemical dosimetry

- Common reaction:
  \( \text{Fe}^{2+} + \text{photon} \rightarrow \text{Fe}^{3+} + e^- \) – Fricke dosimeter
  \( G = 15.4 \text{ molecules/100 eV for x rays or } \gamma \text{ rays} \)
  Measure \( \text{Fe}^{3+} \) concentration by measuring transmission of uv light

Chemical dosimetry

- Disadvantages:
  - Requires large doses (50 – 500 Gy)

- Advantages:
  - Absolute measurement
  - Can measure dose to irregularly shaped volumes
Gel dosimetry

• Early application – Fe$^{2+}$ ions in gel matrix
  – Change to Fe$^{3+}$ gives rise to change in paramagnetic properties
  – Quantify using MRI – T1 parameter can be related to dose
  – Limitations due to diffusion of Fe$^{3+}$ ions through gel

Gel dosimetry

• Maryanski et al – 1993
  – Radiation-induced polymerization of acrylamide gels
  – Polymerization affects optical characteristics
  • Measure degree of polymerization via optical computed tomography

Gel dosimetry

• Applications
  – Dosimetry in 3D volumes – verify dose distribution from complicated beam arrangements

Photo courtesy of G. Ibbott, Ph.D.
**Gel dosimetry**

- **Applications**
  - Brachytherapy dose distributions
  - Neutron and other particle dose distributions

- **Problems**
  - Presence of oxygen adversely affects some polymerizations
  - Absence of heterogeneities
  - Cost

**Thermoluminescent dosimetry**

- Radiation excites electrons to metastable energy levels in crystals
- Heat causes electrons to return to ground state giving off light
- Amount of light proportional to radiation received
Thermoluminescent dosimetry

• Generally use LiF – $Z_{eff} = 8.18$
• Compares with soft tissue (7.4) or air (7.65)
• Slight energy dependence

Thermoluminescent dosimetry

• Disadvantages:
  – Must be calibrated at correct energy

• Advantages:
  – Ease of handling, compact size
  – Measurement can take place some time after irradiation
  – High accuracy – better than 1%

Thermoluminescent dosimetry

• Applications:
  – Routine *in vivo* dosimetry
  – Intercomparisons