The Scientific Medical Effects of Ionizing Radiation Course, conducted once a year, focuses on the latest research about the medical effects of ionizing radiation to help clinicians, health physicists, and medical planners preserve troop health in the face of radiological/nuclear terrorism or warfare.

For additional information about AFRRI training opportunities, contact AFRRI Military Medical Operations at 301-295-9150 or press the “Request info about: MEIR courses” button on this web page. To view more AFRRI information products, go to this web page.

For questions or more information about the content of this presentation, contact the presentation author.
**Fundamentals of Radiation Physics**

1. **REPORT DATE**
   JUL 2008

2. **REPORT TYPE**

3. **DATES COVERED**
   00-00-2008 to 00-00-2008

4. **TITLE AND SUBTITLE**
   Fundamentals of Radiation Physics

5a. **CONTRACT NUMBER**

5b. **GRANT NUMBER**

5c. **PROGRAM ELEMENT NUMBER**

5d. **PROJECT NUMBER**

5e. **TASK NUMBER**

5f. **WORK UNIT NUMBER**

7. **PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
   Uniformed Services University of the Health Sciences, Armed Forces Radiobiology Research Institute (AFRRI), 8901 Wisconsin Avenue BG 42, Bethesda, MD, 20889-5603

8. **PERFORMING ORGANIZATION REPORT NUMBER**

9. **SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

10. **SPONSOR/MONITOR’S ACRONYM(S)**

11. **SPONSOR/MONITOR’S REPORT NUMBER(S)**

12. **DISTRIBUTION/AVAILABILITY STATEMENT**
   Approved for public release; distribution unlimited

13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT**

15. **SUBJECT TERMS**

16. **SECURITY CLASSIFICATION OF:**
   a. **REPORT** unclassified
   b. **ABSTRACT** unclassified
   c. **THIS PAGE** unclassified

17. **LIMITATION OF ABSTRACT**
   Same as Report (SAR)

18. **NUMBER OF PAGES**
   31

19a. **NAME OF RESPONSIBLE PERSON**

---

*Standard Form 298 (Rev. 8-98)*

Prepared by ANSI Std Z39-18
Objectives

- Define ionizing radiation
- Describe sources of ionizing radiation
- Describe interaction of ionizing radiation with matter at microscopic level
- Describe interaction of ionizing radiation with matter at macroscopic level
Categories of Ionizing Radiation

- Directly ionizing
  - Charged particles
  - $e^-$, $e^+$, $p^+$, $\alpha^{++}$, $\pi^-$, heavy nuclei
    - $\alpha^{++} = ^4\text{He}^{+2}$
- Indirectly ionizing
  - Photons
    - $E = h\nu$ (Greek letter $\nu$ = frequency)
  - $\gamma$ rays = photons of nuclear origin
  - Neutrons
Sources of Ionizing Radiation

- Electrically generated
  - Charged particle accelerators
    - Van de Graaff generator, cyclotron
    - linear accelerator, synchrotron, betatron, microtron, rhodotron
- Radionuclides
  - Atom with an unstable nucleus
    - Naturally occurring
    - Man-made (induced)
Basic Nuclear Physics

- Nuclei have different energy states
  - Ground state
  - Metastable or isomeric nuclear states
    - Often $> 10^{-12}$ sec or on the order of hours
  - Excited nuclear states
    - Usually $< 10^{-12}$ sec

- Terminology
  - Isotopes: same Z (atomic number)
  - Isobars: same A (atomic mass)
  - Isotones: same N (number of neutrons)
Nuclear Processes

- $\beta^-$ decay
  - $n \rightarrow p^+ + e^- + \text{antineutrino} + KE$

- $\beta^-, \gamma$ decay
  - $n \rightarrow p^+ + e^- + \text{antineutrino} + KE$
  - followed by $\gamma$ release

- $\beta^+$ decay
  - $p^+ \rightarrow n + e^+ + \text{neutrino} + KE$
  - followed by $e^+/e^-$ annihilation

- $\beta^+, \gamma$ decay
  - $p^+ \rightarrow n + e^+ + \text{neutrino} + KE$
  - followed by $\gamma$ release and $e^+/e^-$ annihilation
More Nuclear Processes

- Electron capture
  - \( p^+ + e^- \rightarrow n + \text{neutrino} + KE \)
    then characteristic x-rays or Auger electrons

- Electron capture, \( \gamma \)
  - \( p^+ + e^- \rightarrow n + \text{neutrino} + KE \)
    followed by \( \gamma \) release
    then characteristic x-rays or Auger electrons

- \( \alpha \) decay

- \( \alpha \) decay, \( \gamma \)
  followed by \( \gamma \) release
Basic Mathematical Formulation

- \( -\frac{dN}{dt} = \lambda N \) (\( \lambda \) = decay constant)
- \( \frac{N(t)}{N_0} = e^{-\lambda t} \)
- \( N(t) = N_0 e^{-\lambda t} \)
- Activity is defined as \( -\frac{dN}{dt} \)
- \( A(t) = A_0 e^{-\lambda t} \)
- \( \ln 2 = \lambda T_{1/2} \) (\( T_{1/2} \) = half life)
- \( 0.693 = \lambda T_{1/2} \)
- \( \lambda = \frac{0.693}{T_{1/2}} \)
- Often useful to use \( e^{-x} \) where \( x = \frac{0.693}{T_{1/2}} t \)
- For small values of \( \lambda t \): \( e^{-\lambda t} \approx 1 - \lambda t \)
- Average lifetime: \( \tau = \frac{1}{\lambda} = 1.44T_{1/2} \)
International System of Units (SI) and Radionuclide Activity & Decay

- SI unit of activity is becquerel (Bq)
- 1 Bq = 1 sec\(^{-1}\)
- Describes rate of decay as number/sec
- Thus 1 Bq = 1 “disintegration” per sec (dps)
- Another unit of activity is the Curie (non-SI)
- 1 Ci = 3.7 x 10\(^{10}\) sec\(^{-1}\) or 3.7 x 10\(^{10}\) Bq
- Therefore 1 Bq = 2.7 x 10\(^{-11}\) Ci
Specific Activity

- Carrier: stable isotopes of the same element in the sample are called carriers.
- Specific activity defined as: radioisotope activity/total mass of element present.
- Units of specific activity (non-SI): Ci/g.
- \( m = \text{activity/specific activity} \).
- Highest possible specific activity is referred to as the carrier free specific activity.
Production of Radionuclides

- Nuclear reactor
  - Neutron activation
  - Not carrier free; tend to decay by $\beta^-$ emission
- Particle accelerator
  - Cyclotron often used to add positive charge
  - Carrier free; tend to decay by $\beta^+$ emission
- Photonuclear
  - Low yield
  - Not carrier free; tend to decay by $\beta^+$ emission
SI Units - Matter - Energy

- Fundamental units of nature (MKS-A)
  length - mass - time - ampere
  meter - kilogram - second - ampere
- Other supplementary units
  temperature (kelvin: K)
  amount of substance (mole: mol)
  luminous intensity (candela: cd)
- All other units are derived
  e.g.: electrical potential (volt)
  \[1 \text{ V} = 1 \text{ m}^2 \text{ kg s}^{-3} \text{ A}^{-1}\]
SI Units - Matter - Energy

- Matter: fundamental property in universe
- Energy: fundamental component of nature
- Energy = ability to do work
- Recall: work = force x distance (newton x meter)
- Energy can be expressed in several ways
- SI unit of energy is joule (J)
- 1 J = 1 m² kg s⁻²
- Total energy = kinetic energy + potential energy
- Consider 1 e- accelerated across an electrical potential of 1 volt acquires a KE of 1 eV
- 1 eV = 1.6022 x 10⁻¹⁹ J
Matter represents a form of potential energy
Mass increases as KE approaches speed of light
An object at rest has its own rest mass energy

\[ m_0c^2 \quad m_e^- \]
\[ e^- \quad 0.511 \text{ MeV} \quad 1 \]
\[ \mu^- \quad 106 \text{ MeV} \quad 207 \]
\[ \pi^- \quad 140 \text{ MeV} \quad 273 \]
\[ p^+ \quad 938.26 \text{ MeV} \quad 1836 \]
\[ n \quad 939.55 \text{ MeV} \quad 1839 \]
Fundamental Quantities

- **Particle fluence**
  \[ \Phi = \frac{dN}{da} \]
- **Energy fluence**
  \[ \Psi = \frac{dE}{da} \]
- **Exposure (roentgen - R)**
  \[ X = \frac{dQ}{dm} \]

where \( dQ \) is the sum of the electrical charges of one sign on all the ions produced in air when all the electrons liberated by photons in a volume of air of mass \( dm \) are completely stopped in air.

\[ 1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg} \]
Principles of Attenuation

- Attenuation = reduction in the number of particles in a radiation beam as it passes through an absorber
- Can occur as a single event or series of events
- Energy loss by an extended series of energy transfer events predominates for charged particle beams
- The concept of range and path length mostly appropriate for charged particle beams
- Energy loss by indirectly ionizing radiation beams can occur in a single event or gradual degradation
- Mean free range & half value thickness of absorber more meaningful for indirectly ionizing radiation
More on Attenuation

- Involves the processes of absorption and scatter
- Based on the concept of a reaction cross section
- Cross section = probability per target per unit area
- Probabilities of independent processes additive
- Attenuation terminology different for charged particle and indirectly ionizing radiation beams
- Charged particle beams scatter elastically
- Energy loss related mostly to inelastic processes
- Linear attenuation coefficient best describes attenuation for indirectly ionizing radiation beams
Energy Loss by Charged Particles

- Predominantly occurs through inelastic collisions with atomic electrons and nuclei
- Involves coulomb force and strong force
- Energy loss per unit length called stopping power
- Depends on particle, its KE, and Z of medium
- KE often symbolized by T
- Stopping power: collisional and radiative
  \[ \frac{dT}{dx} = \frac{dT}{dx_C} + \frac{dT}{dx_R} \]
- Mass stopping power
  \[ \frac{dT}{\rho dx} = \frac{dT}{\rho dx_C} + \frac{dT}{\rho dx_R} \]
Photon Attenuation Processes

- Atomic photoelectric effect
  \[ a_\tau \leftrightarrow \frac{Z^4}{(hv)^3} \text{ x-section/atom for } hv \leq 0.1 \text{ MeV} \]

- Compton scattering
  \[ e_\sigma \leftrightarrow Z \text{ x-sec/electron} \& \ a_\sigma = Z e_\sigma \text{ x-sec/atom} \]
  Compton effect dependent on atomic e\(^-\) density
  Atomic e\(^-\) density mostly constant except for H

- Atomic pair production
  \[ a_\kappa \leftrightarrow Z^2 \text{ cross section/atom} \]

- Rayleigh scattering
  \[ a_\sigma_R \leftrightarrow \frac{(Z/hv)^2}{(Z/hv)^2} \text{ cross section/atom} \]
Photon Attenuation

- Total linear attenuation coefficient
  \[ \mu = \tau + \sigma + \kappa + \sigma_R \]

- Total mass attenuation coefficient
  \[ \frac{\mu}{\rho} = \frac{\tau}{\rho} + \frac{\sigma}{\rho} + \frac{\kappa}{\rho} + \frac{\sigma_R}{\rho} \]

- Under ideal narrow beam conditions
  \[ N(x) = N_0 e^{-\mu x} \] (similar to radioactive decay eqn.)

- Under less ideal conditions (broad beam conditions)
  \[ N(x) = N_0 e^{-\mu' x} \]
  where \( \mu' \) = effective total linear attenuation coefficient
- Photons transfer energy by generating secondary charged particles
- Almost all charged secondary particles are e⁻
- Total energy transfer coefficient
  \[ \mu_{tr} = \tau_{tr} + \sigma_{tr} + \kappa_{tr} + (\gamma,p^+)_{tr} + (\gamma,n)_{tr} \]
- Total mass energy transfer coefficient
  \[ \frac{\mu_{tr}}{\rho} = \frac{\tau_{tr}}{\rho} + \frac{\sigma_{tr}}{\rho} + \frac{\kappa_{tr}}{\rho} + \frac{(\gamma,p^+)}{\rho} + \frac{(\gamma,n)}{\rho} \]
Photon Energy Absorption

- Mass energy absorption coefficient
  \[ \mu_{en}/\rho = (\mu_{tr}/\rho)(1 - g) \]
  where \( g \) = fraction lost to radiative interactions
  \( g \) increases gradually with increasing \( Z \) or \( h\nu \)

- Energy absorbed per unit volume correlates the amount of radiation with the effects of radiation

- Energy deposited per unit length along the track of radiation important and correlates to effects

- Duration of time associated with the delivery of radiation especially important in living systems
  (Above subjects covered shortly or in next lecture)
Kerma and Exposure

- Kerma = kinetic energy released in matter ($K$)
  - $K = K_C + K_R$
  - Energy required to produce a unit charge in air
    $(W/e)_{\text{AIR}} = 33.97 \text{ J/C}$
  - Exposure ($X$) is ionization equivalent of $K_C$ in air
  - Equivalence valid only for photon energies $< 3 \text{ MeV}$
  - $(K_C)_{\text{AIR}} = X(W/e)_{\text{AIR}}$
  - SI units: $X(W/e)_{\text{AIR}} = (\text{C/kg})(\text{J/C}) = \text{J/kg}$
  - Energy per unit mass $\leftrightarrow \text{J/kg}$
  - Roentgen: $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$
  - $1 \text{ C/kg} = 3876 \text{ R}$
Kerma and Dose

- $K = K_C + K_R$
- $K = \frac{dE_{tr}}{dm}$
- $K = E_{tr} \Phi(\mu/\rho) = \Psi(\mu_{tr}/\rho)$
- $K_C = \Psi(\mu_{en}/\rho)$
- SI unit of dose (D) is the Gray (Gy)
  - $1 \text{ Gy} = 1 \text{ J/kg}$ (1 rad = $1 \times 10^{-2} \text{ J/kg} = 100 \text{ cGy}$)
- $D = K_C$ under conditions of CPE
- Charged particle equilibrium is an important and necessary condition for D at the macroscopic level
Neutrons

- Characterized by their kinetic energy $T$
  - Cold neutrons: $5 \times 10^{-5}$ eV $\leq T < 0.025$ eV
  - Thermal neutrons: $T = 0.025$ eV at 293° K
  - Epithermal neutrons: $0.025$ eV $\leq T < 1$ eV
  - Slow neutrons: $1$ eV $\leq T < 1$ keV
  - Intermediate neutrons: $1$ keV $\leq T < 0.5$ MeV
  - Fast neutrons: $0.5$ MeV $\leq T < 10$ MeV
  - High energy neutrons: $10$ MeV $\leq T$

- Neutron beams essentially always occur as mixed photon/neutron beams
Neutrons

- Decay in free space with $T_{1/2} = 10.6$ min according to $n \rightarrow p^+ + e^- + \text{antineutrino}$
- Reacts with other particles predominantly by the strong nuclear force at a range of $10^{-14}$ m
- Interactions produce elastic neutrons, $\gamma$ photons, inelastic neutrons, recoil atoms (nuclei), & fragments
- Neutron kerma $K = \Phi F_n$ with $F_n =$ neutron kerma factor
- Neutron dose $D = K = \Phi F_n$ under conditions of CPE
- Dose effect from neutrons enhanced in living systems
Linear Energy Transfer (LET)

- Recall collisional and radiative stopping power
  \[ \frac{dT}{dx} = \frac{dT}{dx_C} + \frac{dT}{dx_R} \]
- LET equates to a restricted collisional stopping power with energy transfers \( \leq \) a specified value of \( \Delta \)
- \( L_\Delta = (-dT/dx)_C \) with \( E \leq \Delta \)

\[
\begin{align*}
250 \text{ kV}_p \text{ x-rays:} & \quad \text{LET} = 2 \text{ keV/}\mu\text{m} \\
^{60}\text{Co} \gamma \text{ rays:} & \quad \text{LET} = 0.3 \text{ keV/}\mu\text{m} \\
6 \text{ to } 50 \text{ MeV } e^-: & \quad \text{LET} \approx 0.2 \text{ keV/}\mu\text{m} \\
14 \text{ MeV } n: & \quad \text{LET} = 12 \text{ keV/}\mu\text{m} \\
> 100 \text{ MeV } p^+: & \quad \text{LET} = 0.5 \text{ keV/}\mu\text{m} \rightarrow 100 \text{ keV/}\mu\text{m} \\
50 \text{ MeV } \pi^-: & \quad \text{LET} = 0.3 \text{ keV/}\mu\text{m} \rightarrow 100 \text{ keV/}\mu\text{m}
\end{align*}"]
Sievert – SI Unit of Dose Equivalent

- Sievert: $H = DQN$
  - $D =$ absorbed dose (Gy)
  - $Q =$ quality factor
  - $N =$ product of all other dose-modifying factors
    eg: spatial dose distribution or rate of delivery

- $1 \text{ Sv} = 1 \text{ J/kg}$ \hspace{0.5cm} (1 rem = 1 x $10^{-2}$ J/kg = 100 cSv)
  
  250 kV$_p$ x-rays: $Q = 1$
  60Co γ rays: $Q = 1$
  6 to 50 MeV e⁻: $Q = 1$
  14 MeV n: $Q = 10$ if $\geq 10$ keV & $Q = 3$ if $< 10$ keV
  $> 100$ MeV p⁺: $Q = 1$ to $> 10$ as a function of keV
  50 MeV π⁻: $Q = 1$ to $> 10$ as a function of keV
Thank you for your attention

- Questions
- Comments
- Discussion