

Chapter 2

Dosimetric Principles, Quantities and Units

This set of 131 slides is based on Chapter 2 authored by
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of the IAEA publication (ISBN 92-0-107304-6):

**Radiation Oncology Physics:
A Handbook for Teachers and Students**

Objective:

To familiarize students with the basic principles, quantities, and units
used in dosimetry of ionizing radiation.



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CHAPTER 2. TABLE OF CONTENTS

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2.1 INTRODUCTION

- ❑ Radiation dosimetry has its origins in the medical application of ionizing radiation starting with the discovery of x-rays by Röntgen in 1895.
- ❑ In particular,
 - Need of protection against ionizing radiation.
 - Application in medicine.required quantitative methods to determine a "dose of radiation".
- ❑ The purpose of a quantitative concept of a dose of radiation is:
 - To predict associated radiation effects (radiation detriments).
 - To reproduce clinical outcomes.



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2.1 INTRODUCTION

- ❑ The connection to the medical profession is obvious:
 - ➔ The term “dose of radiation” was initially used in a pharmacological sense, i.e., analogously to its meaning when used in prescribing a dose of medicine.
- ❑ Very soon it turned out that physical methods to describe a "dose of radiation" proved superior to any biological methods.



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2.1 INTRODUCTION

- ❑ Radiation dosimetry is now a pure **physical science**.
- ❑ Central are the methods for a quantitative determination of **energy deposited** in a given medium by directly or indirectly ionizing radiations.
- ❑ A number of physical quantities and units have been defined for describing a beam of radiation and the dose of radiation.
- ❑ This chapter deals with the most commonly used **dosimetric quantities** and their **units**.

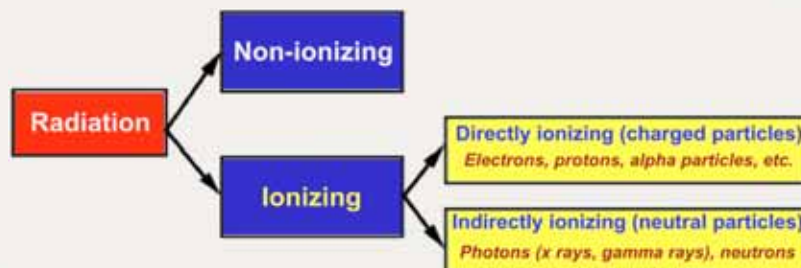


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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.1 Radiation Field

- ❑ Ionizing radiation may simply consist of various types of particles, e.g., photons, electrons, neutrons, protons, etc. From Chapter 1 we know that there are **two main categories of radiation**: ionizing and non-ionizing.



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.1 Radiation Field

- ❑ The term **radiation field** is a very general term that is used to characterize in a quantitative way the radiation in space consisting of particles.
- ❑ There are two very general quantities associated with a radiation field:
 - **Number** N of particles
 - **Energy** R transported by the particles
(which is also denoted as the radiant energy)



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.1 Radiation Field

- ❑ **ICRU-definition of particle number:**
The **particle number** N is the number of particles that are emitted, transferred, or received. Unit: 1
- ❑ **ICRU-definition of radiant energy:**
Radiant energy R is the energy (excluding rest energy) of particles that are emitted, transferred, or received.
Unit: J
- ❑ For particles of energy E (excluding rest energy):

$$R = E \times N$$



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.1 Radiation Field

A detailed description of a radiation field generally will require more information on the particle number N such as:

- of particle type j
- at a point of interest $\vec{r}$
- at energy E
- at time t
- with movement in direction $\vec{\Omega}$


$$N = N_j(\vec{r}, E, t, \vec{\Omega})$$



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.2 Particle Fluence

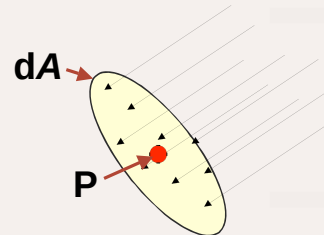
How can the number of particles be determined at a certain point in space?

Consider a point $P(\vec{r})$ in space within a field of radiation.

Then use the following simple method:

In case of a parallel radiation beam, construct a small area dA around the point P in such a way, that its plane is perpendicular to the direction of the beam.

Determine the number of particles that intercept this area dA .



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.2 Particle Fluence

In the general case of **nonparallel** particle directions it is evident that a fixed plane cannot be traversed by all particles perpendicularly.

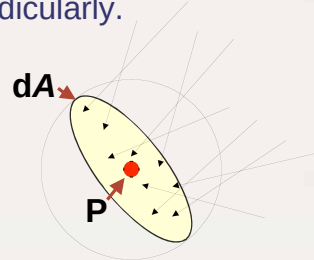


A somewhat modified concept is needed!

The plane dA is allowed to move freely around P , so as to intercept each incident ray perpendicularly.

In practice this means:

- Generate a **sphere** by rotating dA around P
- Count the number of particles **entering** the sphere



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.2 Particle Fluence

- ❑ The ratio between number of particles and the area is called the **fluence** Φ .

- ❑ **Definition:**

The fluence Φ is the quotient dN by dA , where dN is the number of particles incident on a sphere of cross-sectional area dA :

$$\Phi = \frac{dN}{dA} \quad \text{Unit of fluence: m}^{-2}.$$

- ❑ Note: The term **particle fluence** is sometimes also used for **fluence**.



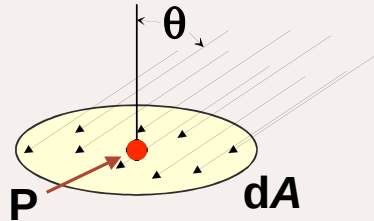
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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.3 Planar Particle Fluence

The definition of **planar particle fluence** refers to the case where the area dA is **not perpendicular** to the beam direction.

- ❑ Planar particle fluence is the number of particles crossing a giving plane per unit area.



- ❑ Planar particle fluence depends on the angle of incidence of the particle beam.



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.4 Energy Fluence

- ❑ The same concept that is used for fluence can also be applied to the radiant energy R :

- ❑ **Definition:**

The energy fluence Ψ is the quotient dR by dA , where dR is the radiant energy incident on a sphere of cross-sectional area dA :

$$\Psi = \frac{dR}{dA}$$

The unit of energy fluence is J/m^2 .



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.4 Energy Fluence

- **Energy fluence** can be calculated from particle fluence by using the following relationship:

$$\Psi = \frac{dN}{dA} \cdot E = \Phi E,$$

where E is the energy of the particle and dN represents the number of particles with energy E .



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.5 Particle Fluence Spectrum

- Almost all realistic photon or particle beams are poly-energetic.



For a better description, the particle fluence is replaced by the particle fluence **differential** in energy:

$$\Phi_E(E) = \frac{d^2N(E)}{dA \cdot dE} = \frac{d\Phi(E)}{dE}$$

The particle fluence differential in energy is also called the **particle fluence spectrum**.



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.6 Energy Fluence Spectrum

The same concept is applied to the **radiant energy R**:

- The energy fluence differential in energy is defined as:

$$\Psi_E(E) = \frac{d\Psi(E)}{dE} = \frac{d\Psi(E)}{dE} \cdot E$$

- The energy fluence differential in energy is also called the **energy fluence spectrum**.



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.6 Energy Fluence Spectrum

Example of Spectra:

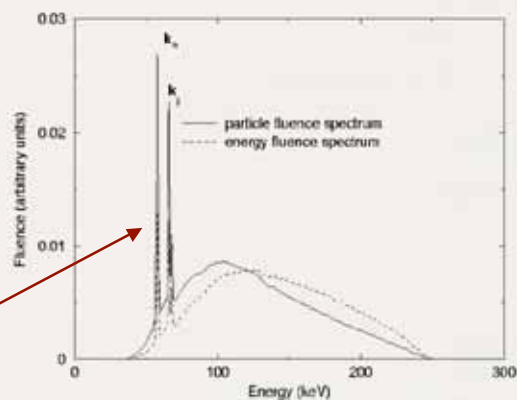
Photon fluence spectrum and energy fluence spectrum generated by an orthovoltage x-ray unit with a kV_p value of 250 kV and an added filtration of 1 mm Al and 1.8 mm Cu.

Target material: tungsten;

Inherent filtration: 2 mm beryllium

Spectra often reflect physical phenomena:

The two spikes superimposed onto the continuous bremsstrahlung spectrum represent the K_α and the K_β characteristic x-ray lines produced in a tungsten target.



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2.2 RADIATION FIELD OR RADIOMETRIC QUANTITIES

2.2.7 Particle Fluence Rate and Energy Fluence Rate

□ The **particle fluence** or the **energy fluence** may change with time.

- For a better description of the time dependence, the fluence quantities are replaced by the fluence quantities **differential** in time:

$$\Phi = \frac{d\Phi}{dt} = \frac{d^2N}{dA \cdot dt}$$

$$\Psi = \frac{d\Psi}{dt} = \frac{d^2R}{dA \cdot dt}$$

Unit: $\text{m}^{-2} \cdot \text{s}^{-1}$

Unit: $\text{J m}^{-2} \cdot \text{s}^{-1}$

- The two fluence quantities differential in time are called the **particle fluence rate** and the **energy fluence rate**. The latter is also referred to as **intensity**.



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.1 General Introduction

The following slides will deal with three dosimetric quantities:

- (1) **Kerma**
- (2) **Cema**
- (3) **Absorbed dose**



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.1 General Introduction

Common characteristics of Kerma, Cema and Absorbed Dose:

- They are generally defined as:

$$\frac{\text{radiation energy (transferred or absorbed)}}{\text{mass}} \left[\frac{\text{J}}{\text{kg}} \right]$$

- They can also be defined as:

$$(\text{radiation field quantity}) \times (\text{mass interaction coefficient}) \left[\frac{\text{J}}{\text{kg}} \right]$$



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.1 General Introduction

- The first characteristic:

$$\text{dosimetric quantity} = \frac{\text{radiation energy (transferred or absorbed)}}{\text{mass}} \left[\frac{\text{J}}{\text{kg}} \right]$$

requires a more detailed inspection into different ways of :

- Radiation energy transfer
- Radiation energy absorption.



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Definition of energy deposit

- ❑ The term "energy deposit" refers to a **single** interaction process
- ❑ The energy deposit ε_i is the energy deposited in a single interaction i

$$\varepsilon_i = \varepsilon_{in} - \varepsilon_{out} + Q \quad \text{Unit: J}$$

where

ε_{in} = the energy of the incident ionizing particle (excluding rest energy)

ε_{out} = the sum of energies of all ionizing particles leaving the interaction (excluding rest energy),

Q = is the change in the rest energies of the nucleus and of all particles involved in the interaction.



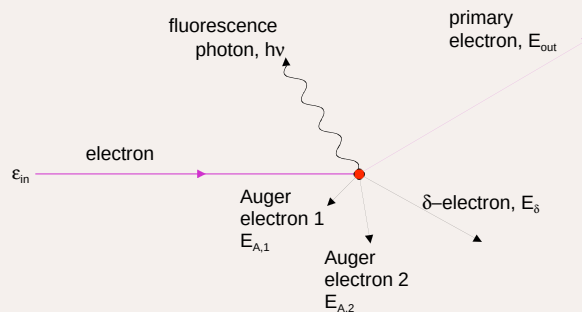
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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Example:

Energy deposit ε_i with $Q = 0$ (electron knock-on interaction):



$$\varepsilon_i = \varepsilon_{in} - (E_{out} + E_{A,1} + E_{A,2} + E_{\delta} + h\nu)$$

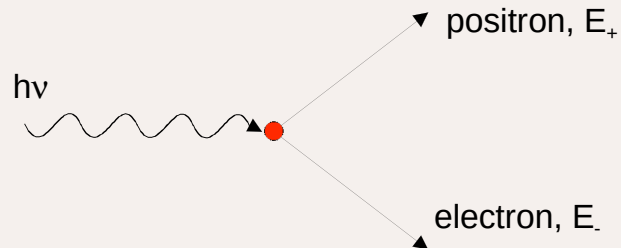


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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Example: Energy deposit ε_i with $Q < 0$ (pair production):



$$\varepsilon_i = hv - (E_+ + E_-) - 2m_0c^2$$

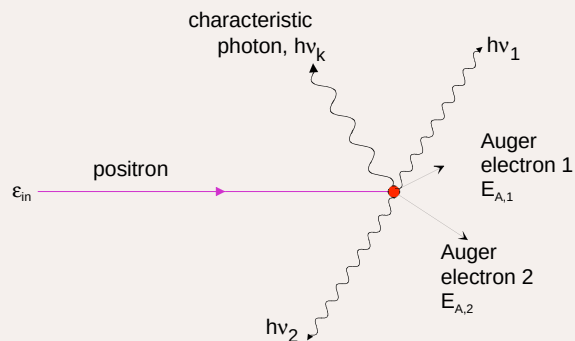


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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Example: Energy deposit ε_i with $Q > 0$ (positron annihilation):



$$\varepsilon_i = \varepsilon_{in} - (hv_1 + hv_2 + hv_k + E_{A,1} + E_{A,2}) + 2m_0c^2$$



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Definition of energy imparted

- ❑ The term "energy imparted" refers to a **small volume**.
- ❑ The energy imparted, ϵ , to matter in a given volume is the **sum of all energy deposits** in the volume, i.e. the sum of energy imparted in all those basic interaction processes which have occurred in the volume during a time interval considered:

$$\epsilon = \sum_i \epsilon_i$$

where the summation is performed over all energy deposits ϵ_i in that volume.

- ❑ **Example:** A radiation detector responds to irradiation with a signal M which is basically related to the energy imparted ϵ in the detector volume.



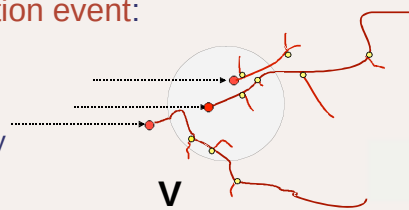
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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Definition of an energy impartation event:

Consider the energy imparted in a volume V by secondary electrons which are generated by primary photons.



- ❑ The incoming **primary photons** are statistically **uncorrelated**.
- ❑ The secondary electrons generated by different photons are **uncorrelated**.
- ❑ However, there is a correlation: When a particular secondary electron is slowing down, it creates further secondary electrons. The **primary generating photon**, the **generated electron** and all **further electrons** (all generations) are **correlated**.

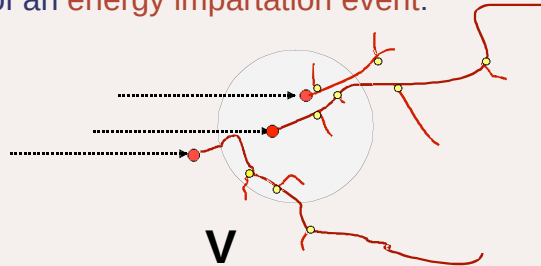


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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Definition of an **energy impartation event**:



- Therefore, all single energy deposits:
 - that are caused from an initially generated secondary electron, and
 - that originate from all further generations of secondary electrons are correlated in time.



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.2 Fundamentals of the Absorption of Radiation Energy

Definition of an **(energy impartation) event**:

- The imparted energy from statistically correlated particles can be put together.
- The term "event" was introduced to denote the imparting of energy ϵ by those statistically correlated energy deposits:

where

N = number of events

n_j = number of energy deposits at event j

$$\epsilon = \sum_{j=1}^N \left(\sum_{i=1}^{n_j} \epsilon_i \right)$$

individual events different in size

Note: The **same amount** of imparted energy ϵ can consist of:

- a small number of events each with a large size
- a high number of events each with a small size



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.3 Stochastic of Energy Absorption

- ❑ Since all energy deposits ϵ_i are of stochastic nature, ϵ is also a stochastic quantity, the values which follow a probability distribution.
- ❑ **Stochastic of Energy Absorption** means that the energy imparted is always **statistically distributed** during the time interval considered.
- ❑ The statistical distribution comes from two sources:
 - fluctuation in the number of events
 - fluctuations in the size of events



The determination of the variance of energy absorption must take into account these two sources!



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.3 Stochastic of Energy Absorption

The combined relative variance of energy imparted ϵ is given by:

$$\frac{V(\epsilon)}{(\bar{\epsilon})^2} = \frac{V(N)}{E^2(N)} + \frac{1}{E(N)} \cdot \frac{V_1(\epsilon)}{E_1^2(\epsilon)}$$

variance of the number
of events

variance of the single
event sizes

where: E = expectation value E_1 = single event exp. value
 N = number of events ϵ = energy imparted



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.3 Stochastic of Energy Absorption

If N (the number of independent tracks) is distributed according to the Poisson distribution (which is very often the case) then: $V(N) = E(N) = N$

$$\Rightarrow V(\varepsilon) = \frac{(\bar{\varepsilon})^2}{N} \cdot \left(1 + \frac{V_1(\varepsilon)}{E_1^2(\varepsilon)} \right)$$

It follows: The variance of the energy imparted ε **increases** with **decreasing** number of events.



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.3 Stochastic of Energy Absorption

General conclusions:

The variance of the energy imparted ε is large

- ☐ for **small volumes**
- ☐ for **small time intervals**
- ☐ for **high LET radiation**
(because the imparted energy ε consists of large event sizes)

Note:

Since a radiation detector responds to irradiation with a signal related to ε , the same conclusions apply to the detector signal.



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.4 Energy Absorption and Energy Transfer

What is the exact meaning of "energy absorption" ?

The term energy absorption refers to **charged particles**, e.g., electrons, protons, etc.

From Chapter 1 we know:

- ❑ Inelastic collisions between an incident electron and an orbital electron are Coulomb interactions resulting in:
 - **Atomic ionization:**
Ejection of the orbital electron from the absorber atom.
 - **Atomic excitation:**
Transfer of an atomic orbital electron from one allowed orbit (shell) to a higher level allowed orbit
- ❑ Atomic ionizations and excitations result in collision **energy** losses experienced by the incident electron and are characterized by **collision (ionization) stopping power**.



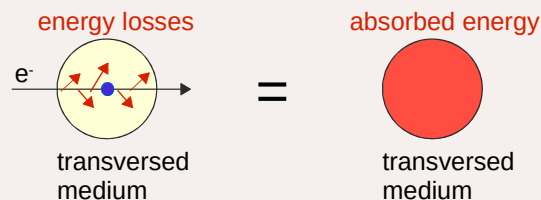
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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.4 Energy Absorption and Energy Transfer

Continued: What is the exact meaning of "energy absorption" ?

- ❑ The **loss of energy** experienced by the incident electron by a collision is at the same time **absorbed** by the absorber atom and thus by a medium.



- ❑ For charged particles, the process of energy absorption in a medium is therefore described by the process of the collision energy loss (the collision stopping power).



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.4 Energy Absorption and Energy Transfer

What is the exact meaning of "energy transfer" ?

The term energy transfer refers to **uncharged particles**, e.g., photons, neutrons, etc.

From Chapter 1 we know:

- The photon fate after an interaction with an atom includes two possible outcomes:
 - **Photon disappears** (i.e., is absorbed completely) and a portion of its energy is transferred to light **charged particles** (electrons and positrons in the absorbing medium).
 - **Photon is scattered** and two outcomes are possible:
 - The resulting photon has the same energy as the incident photon and no light charged particles are released in the interaction.
 - The resulting scattered photon has a lower energy than the incident photon and the energy excess is transferred to a light **charged particle** (electron).



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.4 Energy Absorption and Energy Transfer

Continued: What is the exact meaning of "energy transfer" ?

- The energy that is transferred in a photon interaction to a light charged particle (mostly a secondary electron) is called an energy transfer.
- This process is described by the **energy transfer coefficient**

$$\mu_{tr} = \mu \frac{\bar{E}_{tr}}{h\nu}$$

with $\bar{E}_{tr}$ the average energy transferred from the primary photon with energy $h\nu$ to kinetic energy of charged particles (e^- and e^+).



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2.3 DOSIMETRIC QUANTITIES: FUNDAMENTALS

2.3.4 Energy Absorption and Energy Transfer

Relation between "energy transfer " and "energy absorption "

- ❑ For charged particles, most of the energy loss is directly absorbed
→ energy absorption
- ❑ For uncharged particles, energy is transferred in a first step to (secondary) charged particles → energy transfer.

In a second step, the secondary charged particles lose their energy according to the general behavior of charged particles (again energy absorption).

The energy of uncharged particles like photons or neutrons is imparted to matter in a two stage process.



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2.4 DOSIMETRIC QUANTITIES

2.4.1 Kerma

- ❑ Kerma is an acronym for Kinetic Energy Released per unit Mass.
- ❑ It quantifies the average amount of energy transferred in a small volume from the indirectly ionizing radiation to directly ionizing radiation without concerns to what happens after this transfer.

$$K = \frac{d\bar{E}_{tr}}{dm}$$

- ❑ The unit of kerma is joule per kilogram (J/kg).
- ❑ The name for the unit of kerma is the gray (Gy), where 1 Gy = 1 J/kg.
- ❑ Kerma is a quantity applicable to indirectly ionizing radiations, such as photons and neutrons.



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2.4 DOSIMETRIC QUANTITIES

2.4.1 Kerma

- ❑ The energy transferred to electrons by photons can be expended in two distinct ways:
 - through **collision interactions** (soft collisions and hard collisions);
 - through **radiation interactions** (bremsstrahlung and electron–positron annihilation).
- ❑ The total kerma is therefore divided into two components:
 - Collision kerma K_{col}
 - Radiation kerma K_{rad}

$$K = K_{\text{col}} + K_{\text{rad}}$$

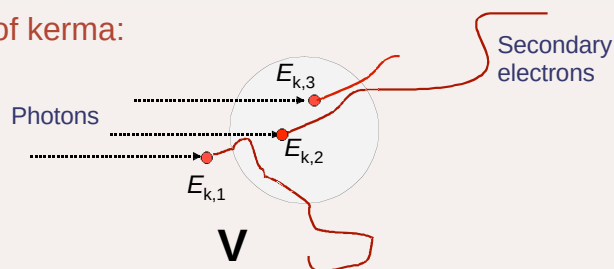


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2.4 DOSIMETRIC QUANTITIES

2.4.1 Kerma

Illustration of kerma:



Collision energy transferred in volume V: $E_{\text{tr}} = E_{k,2} + E_{k,3}$

where E_k is the initial kinetic energy of the secondary electrons.

Note: $E_{k,1}$ is transferred **outside the volume** and is therefore not taken into account in the definition of kerma.



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2.4 DOSIMETRIC QUANTITIES

2.4.1 Kerma

- ❑ The average fraction of energy which is transferred to electrons and then lost through radiation processes is represented by a factor referred to as the radiation fraction $\bar{g}$.
- ❑ The fraction of energy **lost through collisions** is $(1 - \bar{g})$.
- ❑ A frequently used relation between collision kerma K_{col} and total kerma K may be written as follows:

$$K_{\text{col}} = K \cdot (1 - \bar{g})$$



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2.4 DOSIMETRIC QUANTITIES

2.4.1 Kerma

- ❑ Since kerma refers to the average amount of energy $\bar{E}_{\text{tr}}$, it is a **non-stochastic quantity**.
- ❑ This implies that kerma is:
 - steady in space and time
 - differentiable in space and time



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.1 Slide 5 (44/131)

2.4 DOSIMETRIC QUANTITIES

2.4.2 Cema

- ❑ Similar to kerma, cema C is an acronym for **C**onverted **E**nergy per unit **M**Ass.
- ❑ It quantifies the **average amount of energy** converted in a small volume from directly ionizing radiation, such as electrons and protons in collisions with atomic electrons without concerns about what happens after this transfer.

$$C = \frac{d\bar{E}_c}{dm}$$

- Unit of cema is joule per kilogram (J/kg).
- Name for the unit of kerma is the gray (Gy).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.2 Slide 1 (45/131)

2.4 DOSIMETRIC QUANTITIES

2.4.2 Cema

Cema differs from **kerma** in that:

- ❑ Cema involves the energy lost in electronic collisions by the **incoming charged** particles.
- ❑ Kerma involves the energy imparted to **outgoing charged** particles.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.2 Slide 2 (46/131)

2.4 DOSIMETRIC QUANTITIES

2.4.3 Absorbed dose

- ❑ Absorbed dose is a quantity applicable to both indirectly and directly ionizing radiations.
- ❑ **Indirectly ionizing** radiation implies that the energy is imparted to matter in a two step process.
 - In the first step (resulting in kerma), the indirectly ionizing radiation transfers energy as kinetic energy to secondary charged particles.
 - In the second step, these charged particles transfer a major part of their kinetic energy to the medium (finally resulting in absorbed dose).
- ❑ **Directly ionizing** radiation implies that charged particles transfer a major part of their kinetic energy directly to the medium (resulting in absorbed dose).

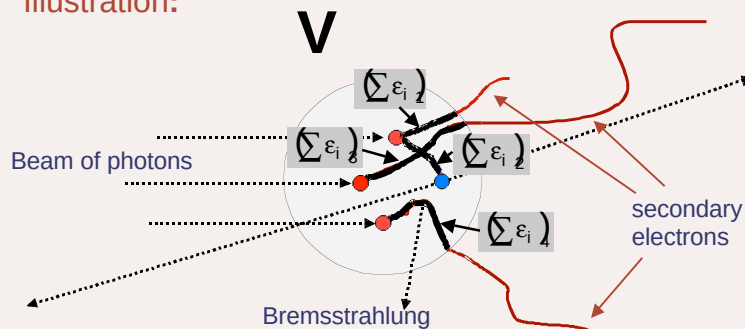


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.3 Slide 1 (47/131)

2.4 DOSIMETRIC QUANTITIES

2.4.3 Absorbed dose

Illustration:



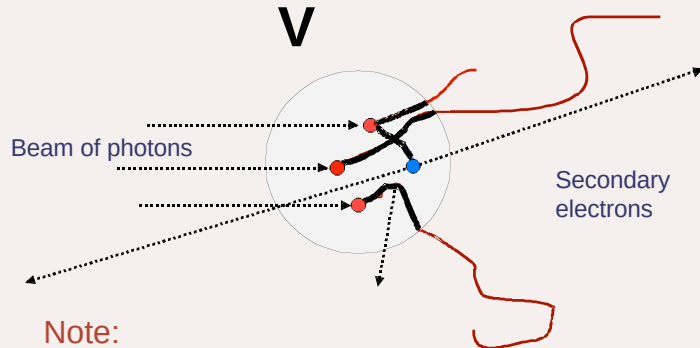
Energy absorbed in volume $V = (\sum \epsilon_i)_1 + (\sum \epsilon_i)_2 + (\sum \epsilon_i)_3 + (\sum \epsilon_i)_4$
where $(\sum \epsilon_i)$ is the sum of energy lost by collisions along the track of the secondary particles **within volume V** .



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.3 Slide 2 (48/131)

2.4 DOSIMETRIC QUANTITIES

2.4.3 Absorbed dose



Note:

Because electrons are traveling in the medium and deposit energy along their tracks, the absorption of energy (= —) does not take place at the same location as the transfer of energy described by kerma (= •).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.3 Slide 3 (49/131)

2.4 DOSIMETRIC QUANTITIES

2.4.3 Absorbed dose

- ☐ Just like kerma and cema, the **absorbed dose** is a non-stochastic quantity.
- ☐ Absorbed dose D is related to the stochastic quantity average energy imparted $\bar{\epsilon}$ by:

$$D = \frac{d\bar{\epsilon}}{dm}$$

- ☐ The unit of absorbed dose is joule per kilogram (J/kg).
- ☐ The name for the unit of absorbed dose is the gray (Gy).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.4.3 Slide 4 (50/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

- ❑ Since **dosimetric quantities** can also be defined as a product of

$$\text{radiation field quantity} \times \text{mass interaction coefficient} \left[\frac{\text{J}}{\text{kg}} \right]$$

this concept requires an inspection into the interaction coefficients of radiation.

- ❑ The following slides refer to electrons and photons. They include some repetitions taken from Chapter 1.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5 Slide 1 (51/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

From Chapter 1 we know:

- ❑ As an energetic electron traverses matter, it undergoes Coulomb interactions (collisions) with absorber atoms, i.e., with:
 - Atomic orbital electrons
 - Atomic nuclei
- ❑ Through these collisions the electrons may:
 - Lose their kinetic energy (**collision and radiation loss**)
 - Change direction of motion (**scattering**)



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 1 (52/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- ❑ Energy losses are described by **stopping power**.
- ❑ Scattering is described by **angular scattering power**.
- ❑ Collision between the incident electron and an absorber atom may be:
 - Elastic
 - Inelastic



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 2 (53/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- ❑ In an **elastic collision** the incident electron is deflected from its original path but no energy loss occurs.
- ❑ In an **inelastic collision** with orbital electron the incident electron is deflected from its original path and loses part of its kinetic energy.
- ❑ In an **inelastic collision with nucleus** the incident electron is deflected from its original path and loses part of its kinetic energy in the form of **bremsstrahlung**.

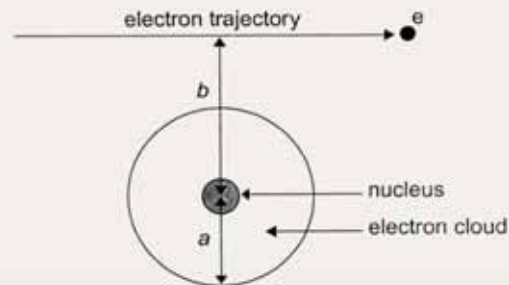


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 3 (54/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- The type of inelastic interaction that an electron undergoes with a particular atom of radius a depends on the impact parameter b of the interaction.

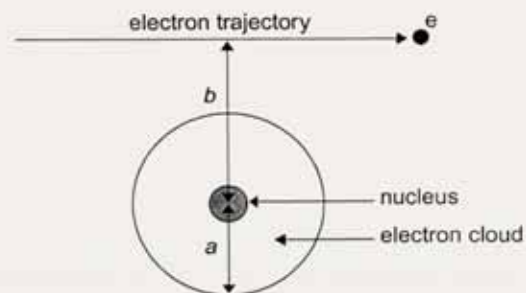


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 4 (55/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- For $b \gg a$, the incident electron will undergo a **soft collision** with the whole atom and only a small amount of its kinetic energy (few %) will be transferred from the incident electron to orbital electron.

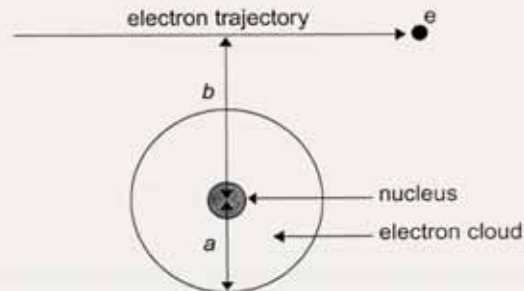


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 5 (56/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- For $b \approx a$ the electron will undergo a **hard collision** with an orbital electron and a significant fraction of its kinetic energy (up to 50%) will be transferred to the orbital electron.

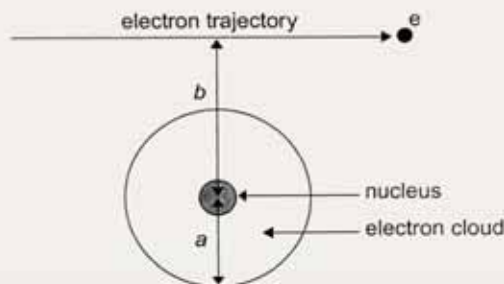


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 6 (57/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- For $b < \frac{1}{2}a$ the incident electron will undergo a **radiation collision** with the atomic nucleus and emit a bremsstrahlung photon with energy between 0 and the incident electron kinetic energy.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 7 (58/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.1 Electron interactions

- ❑ Inelastic collisions between the incident electron and an orbital electron are Coulomb interactions that result in:
 - **Atomic ionization:**
Ejection of the orbital electron from the absorber atom.
 - **Atomic excitation:**
Transfer of an atomic orbital electron from one allowed orbit (shell) to a higher level allowed orbit.
- ❑ Atomic ionizations and excitations result in collision energy losses experienced by incident electron and are characterized by **collision (ionization) stopping power**.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.1 Slide 8 (59/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.2 Electrons: Stopping power for charged particles

- ❑ The total energy loss by incident charged particles through inelastic collisions is described by the

total linear stopping power S_{tot}

which represents the average rate of kinetic energy loss E_K by the electron per unit path length x :

$$S_{\text{tot}} = \frac{dE_K}{dx} \quad \text{in MeV/cm}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.2 Slide 1 (60/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.3 Electrons: Mass stopping power

- Division by the density of the absorbing medium almost eliminates the dependence of the mass stopping power on mass density,
- Total mass stopping power $(S / \rho)_{\text{tot}}$ is defined as the linear stopping power divided by the density of the absorbing medium.

$$\left(\frac{S}{\rho} \right)_{\text{tot}} = \frac{1}{\rho} \frac{dE_K}{dx} \quad \text{in MeV.cm}^2/\text{g}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.3 Slide 1 (61/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.3 Electrons: Mass stopping power

- The total mass stopping power $(S / \rho)_{\text{tot}}$ consists of two components:
 - Mass collision stopping power $(S / \rho)_{\text{col}}$ resulting from electron-orbital electron interactions (atomic ionizations and atomic excitations)
 - Mass radiation stopping power $(S / \rho)_{\text{rad}}$ resulting mainly from electron-nucleus interactions (bremsstrahlung production)

$$\left(\frac{S}{\rho} \right)_{\text{tot}} = \left(\frac{S}{\rho} \right)_{\text{col}} + \left(\frac{S}{\rho} \right)_{\text{rad}}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.3 Slide 2 (62/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.3 Electrons: Mass stopping power

- ❑ Stopping powers are rarely measured, rather they are calculated from theory.
- ❑ The Bethe theory is used to calculate stopping powers for soft collisions.
- ❑ For electrons and positrons, energy transfers due to soft collisions are combined with those due to hard collisions using the Møller (for electrons) and Bhabha (for positrons) cross-sections for free electrons.
- ❑ Complete mass collision stopping power for electrons and positrons is taken from the ICRU Report No. 37.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.3 Slide 3 (63/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.4 Mass stopping power for electrons and positrons

- ❑ Formula according to the ICRU Report No. 37.

$$\frac{S_{\text{col}}}{\rho} = \frac{N_A Z}{A} \frac{\pi r_0^2 2 m_e c^2}{\beta^2} \left[\ln(E_K / I)^2 + \ln(1 + \tau / 2) + F^\pm(\tau) - \delta \right]$$

with

N_A	=	Avogadro's constant	I	=	mean excitation energy
Z	=	atomic number of substance	$\tau = E_K / (m_e c^2)$		
A	=	molar mass of substance	δ	=	density effect correction
r_0	=	electron radius			
$m_e c^2$	=	rest energy of the electron			
β	=	v/c			
v	=	velocity of electron	$F^\pm$	=	given in
c	=	velocity of light			the next slide



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.4 Slide 1 (64/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.4 Mass stopping power for electrons and positrons

F^- for electrons is given as:

$$F^- = (1 - \beta^2) \left[1 + \tau^2 / 8 - (2\tau + 1) \ln 2 \right]$$

F^+ for positrons is given as:

$$F^+ = 2 \ln 2 - (\beta^2 / 12) \left[23 + 14 / (\tau + 2) + 10 / (\tau + 2)^2 + 4 / (\tau + 2)^3 \right]$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.4 Slide 2 (65/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.4 Mass stopping power for electrons and positrons

- ❑ The mean **excitation potential** I is a geometric mean value of all ionization and excitation potentials of an atom of the absorbing material.
- ❑ I values are usually derived from measurements of stopping powers in heavy charged particle beams, for which the effects of scattering in these measurements is minimal.
 - For elemental materials I varies approximately linearly with Z , with, on average, $I = 11.5 \times Z$.
 - For compounds, I is calculated assuming additivity of the collision stopping power, taking into account the fraction by weight of each atom constituent in the compound.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.4 Slide 3 (66/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.4 Mass stopping power for electrons and positrons

- Selected data on the mean excitation potential I , as given in the ICRU Report No. 37

Substance	Excitation potential in eV
hydrogen (molecular gas)	19.2
carbon (atomic gas)	62.0
nitrogen (molecular gas)	82.0
oxygen (molecular gas)	95.0
air	85.7
water, liquid	75.0

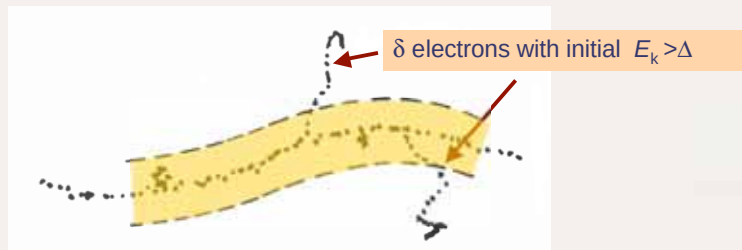


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.4 Slide 4 (67/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.5 Concept of restricted stopping power

Track of an electron:



Generate a tube around the track such that the radius of the tube includes the start energy of δ electrons up to a maximum energy Δ .

δ electrons with a starting energy $E_k > \Delta$ are excluded.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.5 Slide 1 (68/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.5 Mass stopping power for electrons and positrons

Definition of **restricted stopping power** for charged particles:

- The restricted linear collision stopping power L_{Δ} of a material is the quotient of dE_{Δ} by $d\ell$, where dE_{Δ} is the energy lost by a charged particle due to soft and hard collisions in traversing a distance $d\ell$ **minus** the total kinetic energy of the charged particles released with kinetic energies in excess of Δ :

$$L_{\Delta} = \frac{dE_{\Delta}}{d\ell}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.5 Slide 2 (69/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.5 Mass stopping power for electrons and positrons

- **Note:** As the threshold for maximum energy transfer in the restricted stopping power increases, the restricted mass stopping power tends to the unrestricted mass stopping power for $\Delta \rightarrow E_K/2$.
- **Note:** Since energy transfers to secondary electrons are limited to $E_K/2$, unrestricted and restricted electron mass stopping powers are identical for kinetic energies lower than or equal to 2Δ .

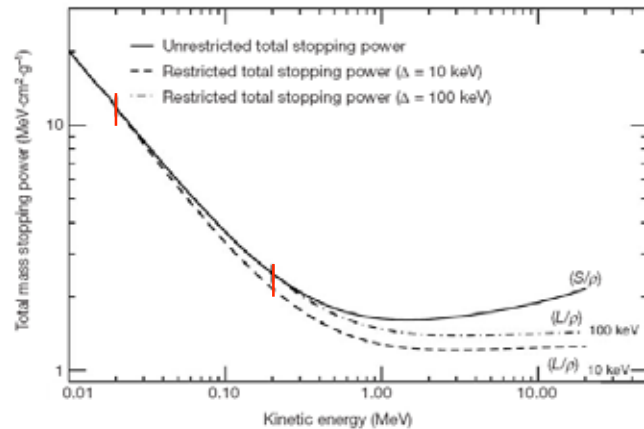


Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.5 Slide 3 (70/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.5 Mass stopping power for electrons and positrons

Unrestricted and restricted ($\Delta = 10$ and 100 keV) total mass stopping powers for carbon (from ICRU Report No. 37)



Vertical lines in red indicate the points at which restricted and unrestricted mass stopping powers begin to diverge as the kinetic energy increases.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.5 Slide 4 (71/131)

2.5 INTERACTION COEFFICIENTS: ELECTRONS

2.5.5 Mass stopping power for electrons and positrons

The concept of a restricted stopping power is needed:

- ☐ In the **Spencer–Attix cavity theory**.
- ☐ In some radiobiological models.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.5.5 Slide 5 (72/131)

2.6 INTERACTION COEFFICIENTS: PHOTONS

- ❑ The energy that is transferred in an photon interaction to a light charged particle (mostly a secondary electron) is called an energy transfer.
- ❑ The energy transfer process is described by the **energy transfer coefficient**

$$\mu_{tr} = \mu \frac{\bar{E}_{tr}}{h\nu}$$

with $\bar{E}_{tr}$ the average energy transferred from the primary photon with energy $h\nu$ to kinetic energy of charged particles (e^- and e^+).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.6 Slide 1 (73/131)

2.6 INTERACTION COEFFICIENTS: PHOTONS

Repetition:

- ❑ A small part of the energy that is transferred in an photon interaction to a light charged particle leads to:
 - Production of radiative photons as the secondary charged particles slow down and interact with nuclei in the medium.
 - These interactions most prominently are bremsstrahlung as a result of Coulomb field interactions between the charged particle and the atomic nuclei.
- ❑ This lost through radiation processes is represented by the factor $\bar{g}$ referred to as the radiation fraction.
- ❑ The remaining energy is absorbed. This process is described by the **energy absorption coefficient** μ_{en} (or μ_{ab})

$$\mu_{en} = \mu_{tr} (1 - \bar{g})$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.6 Slide 2 (74/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- For monoenergetic photons, the total kerma K at a point in a medium:

$$K = \frac{d\bar{E}_{tr}}{dm}$$

is related to the energy fluence Ψ at that point in the medium by:

$$K = \Psi \cdot \frac{\mu_{tr}}{\rho}$$

where (μ_{tr}/ρ) is the mass–energy transfer coefficient for the monoenergetic photons in the medium.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 1 (75/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- For monoenergetic photons the collision kerma K_{col} at a point in a medium:

$$K_{col} = K \cdot (1 - \bar{g})$$

is related to the energy fluence Ψ at that point in the medium by:

$$K_{col} = \Psi \cdot \frac{\mu_{en}}{\rho}$$

where (μ_{en}/ρ) is the mass–energy absorption coefficient for monoenergetic photons in the medium.



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 2 (76/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- ❑ For **polyenergetic** beams a similar relation exists.
- ❑ If a photon energy fluence spectrum (that is the energy fluence differential in energy), $\Psi_E(E)$ is present at the point of interest, the collision kerma K_{col} at that point is obtained by:

$$K_{\text{col}} = \int_0^{E_{\text{max}}} \Psi_E(E) \cdot \left(\frac{\mu_{\text{en}}}{\rho} \right) dE$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 3 (77/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- ❑ One may use the following shorthand notation for the **mean mass–energy absorption coefficient**.
- ❑ The mass–energy absorption coefficient is **averaged** over the energy fluence spectrum:

$$\left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right) = \frac{\int_0^{E_{\text{max}}} \Psi_E(E) \cdot \left(\frac{\mu_{\text{en}}(E)}{\rho} \right) dE}{\int_0^{E_{\text{max}}} \Psi_E(E) dE}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 4 (78/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- The integral over the energy fluence differential in energy in the denominator is the total energy fluence:

$$\Psi = \int_0^{E_{\max}} \Psi_E(E) dE$$

- Mean mass–energy absorption coefficient is thus given by:

$$\left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right) = \frac{\int_0^{E_{\max}} \Psi_E(E) \cdot \left(\frac{\mu_{\text{en}}(E)}{\rho} \right) dE}{\Psi}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 5 (79/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- It follows from:

$$K_{\text{col}} = \int_0^{E_{\max}} \Psi_E(E) \cdot \left(\frac{\mu_{\text{en}}}{\rho} \right) dE \quad \text{and} \quad \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right) = \frac{\int_0^{E_{\max}} \Psi_E(E) \cdot \left(\frac{\mu_{\text{en}}(E)}{\rho} \right) dE}{\Psi}$$

That the collision kerma is given by:

$$K_{\text{col}} = \Psi \cdot \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 6 (80/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- If one compares the collision kerma between a medium 1 and a medium 2, both at the same energy fluence Ψ , one can obtain the frequently used relation:

$$\frac{K_{\text{col},2}}{K_{\text{col},1}} = \frac{\Psi \cdot \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_2}{\Psi \cdot \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_1} = \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_{2,1}$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 7 (81/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- In some cases where the energy fluence is not equal in medium 1 and medium 2, the fluence ratio $\Psi_{2,1}$ can be assumed to be unity through a proper scaling of dimensions (using the scaling theorem):
- For very similar materials.
 - For situations in which the mass of material 2 is sufficient to provide buildup but at the same time small enough so as not to disturb the photon fluence in material 1 (for example for a dose to a small mass of tissue in air).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.1 Slide 8 (82/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- ❑ The absorbed dose to a medium D_{med} is related to the electron fluence Φ_{med} in the medium as follows:

$$D_{\text{med}} = \Phi \cdot \left(\frac{S_{\text{col}}}{\rho} \right)_{\text{med}}$$

where $(S_{\text{col}}/\rho)_{\text{med}}$ is the unrestricted mass collision stopping power of the medium at the energy of the electron.

- ❑ This relation is valid under the conditions that:
- Radiative photons escape the volume of interest
 - Secondary electrons are absorbed on the spot
 - Or there is a charged particle equilibrium (CPE) of secondary electrons



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.2 Slide 1 (83/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- ❑ Even for monoenergetic starting electron kinetic energy E_K , a primary fluence spectrum is always present owing to electron slowdown in a medium.
- ❑ The spectrum ranges in energy from E_K down to zero.
- ❑ The spectrum is commonly denoted, by $\Phi_{\text{med},E}$.
- ❑ The absorbed dose to a medium D_{med} is then given by;

$$D_{\text{med}} = \int_0^{E_{\text{max}}} \Phi_{\text{med},E}(E) \cdot \left(\frac{S_{\text{col}}(E)}{\rho} \right) dE$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.2 Slide 2 (84/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- One may again use a shorthand notation for the collision stopping power **averaged** over the fluence spectrum:

$$\left(\frac{\bar{S}_{\text{col}}}{\rho} \right)_{\text{med}} = \frac{1}{\Phi_{\text{med}}} \int_0^{E_{\text{max}}} \Phi_{\text{med},E}(E) \cdot \left(\frac{S_{\text{col}}(E)}{\rho} \right)_{\text{med}} dE$$

The collision kerma is then given by:

$$D_{\text{med}} = \Phi_{\text{med}} \cdot \left(\frac{\bar{S}_{\text{col}}}{\rho} \right)$$



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.2 Slide 3 (85/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.1 Energy fluence and kerma (photons)

- If one compares the absorbed dose between a medium 1 and a medium 2, both at the same fluence:

$$\Phi_{\text{med1}} = \Phi_{\text{med2}}$$

one can obtain the frequently used relation:

$$\frac{D_{\text{med}_2}}{D_{\text{med}_1}} = \frac{\Phi_{\text{med}_2} \cdot \left(\frac{\bar{S}_{\text{col}}}{\rho} \right)_{\text{med}_2}}{\Phi_{\text{med}_1} \cdot \left(\frac{\bar{S}_{\text{col}}}{\rho} \right)_{\text{med}_1}} = \left(\frac{\bar{S}_{\text{col}}}{\rho} \right)_{\text{med}_2, \text{med}_1}$$



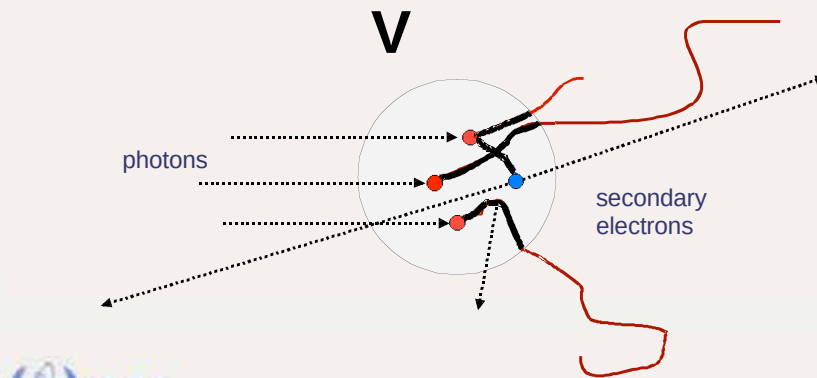
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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.3 Kerma and dose (charged-particle equilibrium)

We know already:

Because electrons travel in the medium and deposit energy along their tracks, this absorption of energy (= —) does not take place at the same location as the transfer of energy described by kerma (= $\bullet$).



Review of Radiation Oncology Physics: A Handbook for Teachers and Students - 2.7.3 Slide 1 (87/131)

2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.3 Kerma and dose (charged-particle equilibrium)

- ❑ Since radiative photons mostly escape from the volume of interest, one relates **absorbed dose** usually to **collision kerma**.
- ❑ Since the secondary electrons released through photon interactions have a non-zero (finite) range, energy may be transported beyond the volume of interest. It follows:

$$K_{\text{col}} \neq D$$

- ❑ The ratio of dose and collision kerma is often denoted as:

$$\beta = D / K_{\text{col}}$$

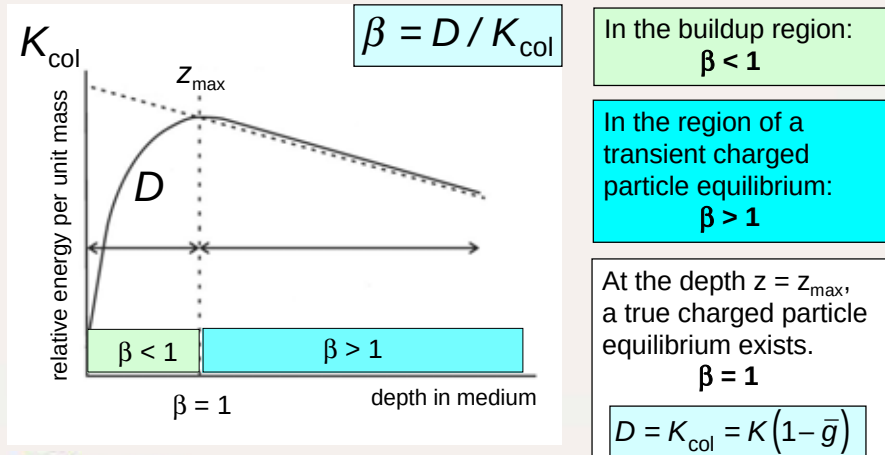


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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.3 Kerma and dose (charged-particle equilibrium)

Relation between collision kerma and absorbed dose



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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.4 Collision kerma and exposure

- Exposure X is the quotient of dQ by dm , where dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photons in mass dm of air are completely stopped in air:

$$X = \frac{dQ}{dm}$$

- The unit of exposure is coulomb per kilogram (C/kg).
 - The old unit used for exposure is the roentgen R, where
 $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$.
 - In the SI system of units, roentgen is no longer used and the unit of exposure is simply $2.58 \times 10^{-4} \text{ C/kg}$ of air.



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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.4 Collision kerma and exposure

- The average energy expended in air per ion pair formed W_{air} is the quotient of E_K by N , where N is the mean number of ion pairs formed when the initial kinetic energy E_K of a charged particle is completely dissipated in air:

$$W_{\text{air}} = \frac{E_K}{N}$$

- The current best estimate for the average value of W_{air} is 33.97 eV/ion pair or $33.97 \times 1.602 \times 10^{19}$ J/ion pair.
- It follows:

$$\frac{W_{\text{air}}}{e} = 33.97 \text{ J/C}$$



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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.4 Collision kerma and exposure

- Multiplying the collision kerma K_{col} by (e/W_{air}) , the number of coulombs of charge created per joule of energy deposited, one obtains the charge created per unit mass of air or exposure:

$$X = (K_{\text{col}})_{\text{air}} \cdot \left(\frac{e}{W_{\text{air}}} \right)$$



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2.7 RELATIONSHIPS BETWEEN DOSIMETRIC QUANTITIES

2.7.4 Collision kerma and exposure

- Since

$$D = K_{\text{col}} K(1 - \bar{g})$$

it follows:

$$K_{\text{air}} = X \cdot \left(\frac{W_{\text{air}}}{e} \right) \frac{1}{1 - \bar{g}}$$

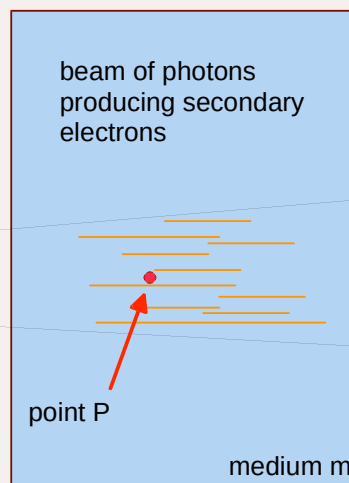


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2.8 CAVITY THEORY

- Consider a point P within a medium m within a beam of photon radiation (right).
- The absorbed dose at point P can be calculated by:

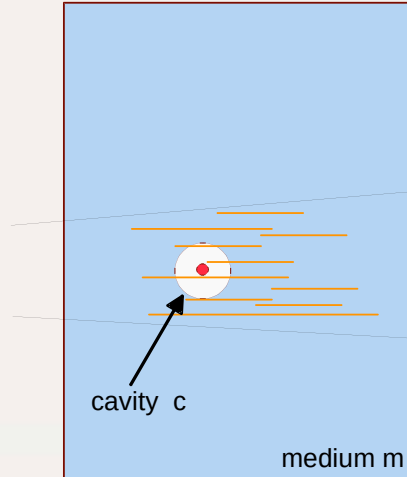
$$D_{\text{med}}(P) = \Phi \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{med}}$$



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2.8 CAVITY THEORY

- ❑ In order to **measure** the absorbed dose at point P in the medium, it is necessary to introduce a radiation sensitive device (dosimeter) into the medium.
- ❑ The sensitive medium of the dosimeter is frequently called a **cavity**.
- ❑ Generally, the sensitive medium of the cavity will not be of the same material as the medium in which it is embedded.



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2.8 CAVITY THEORY

- ❑ The measured absorbed dose D_{cav} within the entire cavity can also be calculated by:

$$D_{\text{cav}} = \int_{V_{\text{cav}}} \int_{E=0}^{E_{\text{max}}} \Phi_{E,\vec{r}}(E,\vec{r}) \frac{S_{\text{cav}}(E)}{\rho} dE d\vec{r}$$

- ❑ If the material of the cavity differs in atomic number and density from that of the medium, the measured absorbed dose to the cavity will be different from the absorbed dose to the medium at point P.

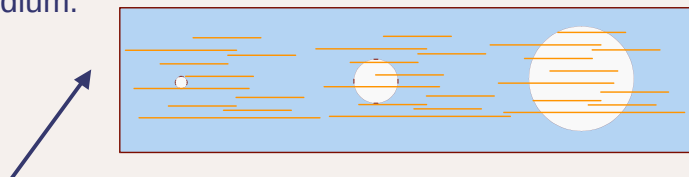
$$D_{\text{cav}} \neq D_{\text{med}}(P)$$



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2.8 CAVITY THEORY

- ❑ Cavity sizes are referred to as **small, intermediate or large** in comparison with the **ranges of secondary charged particles** produced by photons in the cavity medium.



- ❑ The case where the range of charged particles (electrons) is much larger than the cavity dimensions (i.e., the cavity is regarded as small) is of special interest.



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2.8 CAVITY THEORY

- ❑ In order to determine D_m from D_c , various cavity theories have been developed, which depend on the size of the cavity.

Examples are:

- ❑ for small cavities:
 - **Bragg–Gray theory**
 - **Spencer–Attix theory**
- ❑ for cavities of intermediate size:
 - **Burlin theory.**



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

- ❑ The Bragg–Gray (B-G) cavity theory was the first cavity theory developed to provide a relation between the absorbed dose in a dosimeter and the absorbed dose in the medium containing the dosimeter.
- ❑ Two conditions apply for the B-G cavity theory:
 - Condition (1):
The cavity must be small when compared with the range of charged particles incident on it, so that its presence does not perturb the fluence of charged particles in the medium.
 - Condition (2):
The absorbed dose in the cavity is deposited solely by those electrons crossing the cavity.



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

- ❑ The result of condition (1) is that the electron fluences are almost the same and equal to the equilibrium fluence established in the surrounding medium.
- ❑ However:
 - This condition can only be valid in regions of charged particle equilibrium or transient charged particle equilibrium.
 - The presence of a cavity always causes some degree of fluence perturbation that requires the introduction of a fluence perturbation correction factor.



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

□ Condition (2) implies that

- Photon interactions in the cavity are negligible and thus ignored.
- All electrons depositing the dose inside the cavity are produced outside the cavity and **completely cross the cavity**. Such electrons can be called "crossers".
- No secondary electrons are produced inside the cavity (starters) and no electrons stop within the cavity (stoppers).



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

- If one assumes that the energy of the crossers does not change within a small air cavity volume, the dose in the cavity is completely due to the crossers as:

$$D_{\text{cav}} = \int_{E_k=0}^{E_{k0}} \Phi_{E_k}(E_k) \cdot \frac{S(E_k)}{\rho} dE_k$$

where E_k is the kinetic energy of crossers;

E_{k0} is their highest energy equal to the initial energy of the secondary electrons produced by photons;

$\Phi_E(E_k)$ is the energy spectrum of all crossers



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

- Using the shorthand notation we have in the cavity:

$$D_{\text{cav}} = \Phi \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{cav}}$$

- In the medium without the cavity:

$$D_{\text{med}}(P) = \Phi \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{med}}$$

- Since Φ is identical (not disturbed), it follows:

$$D_{\text{med}}(P) = D_{\text{cav}} \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{med}} / \left(\frac{\bar{S}}{\rho} \right)_{\text{cav}} = D_{\text{cav}} \cdot \left(\frac{\bar{S}}{\rho} \right)_{\text{med,cav}}$$



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2.8 CAVITY THEORY

2.8.1 The Bragg-Gray cavity theory

- Bragg-Gray cavity theory therefore says:

"The absorbed dose to the medium at point P can be obtained from measured absorbed dose in the cavity by multiplication with the stopping power ratio $\left(\frac{\bar{S}}{\rho} \right)_{\text{med,cav}}$ "



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- ❑ The Bragg-Gray cavity theory does not take into account the creation of secondary (delta) electrons generated as a result of the slowing down of the primary electrons in the cavity.

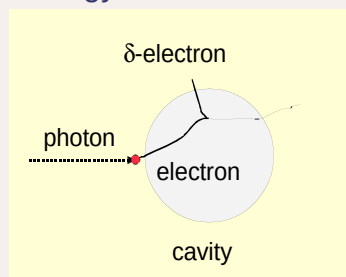


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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- ❑ Some of these electrons released in the gas cavity may have sufficient energy to **escape from the cavity** carrying some of their energy with them out of the volume.



- ❑ This reduces the energy absorbed in the cavity and requires a **modification to the stopping power of the crossers in the gas.**



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- ❑ This is accomplished in the **Spencer-Attix cavity theory** by explicitly considering the δ electrons.
- ❑ Spencer-Attix cavity theory operates under the same two conditions as used in the Bragg-Gray cavity theory.
- ❑ However, these conditions are now applied also to the fluence of the δ electrons.



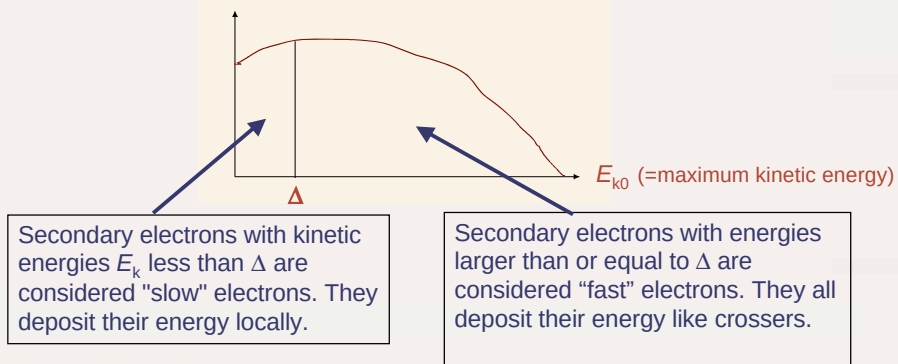
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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

The concept of the Spencer-Attix cavity theory:

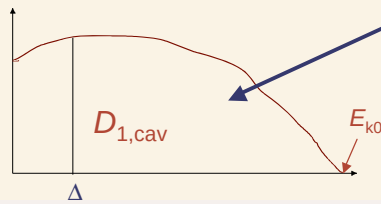
The total secondary electron fluence (crossers and δ electrons) is divided into two components based on a user-defined **energy threshold Δ** .



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory



- All secondary electrons with energies $E_k > \Delta$ are treated as crossers.
- It means that such δ electrons with $E_k > \Delta$ must be included in the entire electron spectrum.

$$\Rightarrow D_{1,cav} = \int_0^{E_{k0}} \Phi_{E_k}^{\delta}(E_k) \cdot \frac{S_{cav}(E_k)}{\rho} dE_k$$

where $\Phi_{E_k}^{\delta}(E_k)$ is now the energy spectrum of all electrons including the δ electrons with $E_k > \Delta$



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- However, this equation

$$D_{1,cav} = \int_0^{E_{k0}} \Phi_{E_k}^{\delta}(E_k) \cdot \frac{S_{cav}(E_k)}{\rho} dE_k$$

is not correct because the energy of the δ electrons is now taken into account twice:

- as part of the spectrum of electrons
- in the unrestricted stopping power as the energy lost ranging up to the maximum energy lost (including that larger than Δ)



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- ❑ Solution to this situation:
The calculation must refer to the **restricted** mass stopping power:

$$L_{\Delta} = \frac{dE_{\Delta}}{d\ell}$$

➔ $D_{1,cav} = \int_0^{E_{k0}} \Phi_{E_k}^{\delta}(E_k) \cdot \frac{L_{\Delta,cav}(E_k)}{\rho} dE_k$

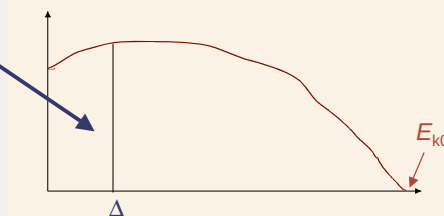


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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- ❑ Secondary electrons with kinetic energies $K_E < \Delta$ are considered slow electrons. They deposit their energy "locally"
- ❑ "Locally" means that they can be treated as so-called "stoppers". $D_{2,cav}$ is sometimes called the "track-end term".
- ❑ Energy deposition of "stoppers" **cannot** be described by stopping power.
- ❑ Their energy lost is simply their (local) kinetic energy.



➔ $D_{2,cav} = \text{energy of stoppers per mass}$



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- For practical calculations, the track-end term TE was approximated by A. Nahum as:

$$TE = \Phi_{E_K}^{\delta}(\Delta) \cdot \frac{S(\Delta)}{\rho} \cdot \Delta$$

- Finally we have:

$$D_{cav} = \int_0^{E_{k0}} \Phi_{E_K}^{\delta}(E_K) \cdot \frac{L_{\Delta,cav}(E_K)}{\rho} dE_K + TE$$



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2.8 CAVITY THEORY

2.8.2 The Spencer-Attix cavity theory

- In the Spencer-Attix cavity theory, the stopping power ratio is therefore obtained by:

$$\left(\frac{\bar{S}}{\rho} \right)_{med,cav} = \frac{\int_0^{E_{k0}} \Phi_{E_K}^{med,\delta}(E_K) \cdot \frac{L_{\Delta,med}(E_K)}{\rho} dE_K + \Phi_{E_K}^{med,\delta}(\Delta) \cdot \frac{S_{med}(\Delta)}{\rho} \cdot \Delta}{\int_0^{E_{k0}} \Phi_{E_K}^{cav,\delta}(E_K) \cdot \frac{L_{\Delta,cav}(E_K)}{\rho} dE_K + \Phi_{E_K}^{cav,\delta}(\Delta) \cdot \frac{S_{cav}(\Delta)}{\rho} \cdot \Delta}$$



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2.8 CAVITY THEORY

2.8.3 Considerations in the application of cavity theory to ionization chamber calibration and dosimetry protocols

- ☐ The value of the energy threshold Δ is set 10 keV.
- ☐ In the context of cavity theories, the sensitive volume of the dosimeter can be identified as the “cavity”, which may contain a gaseous, liquid or solid medium (e.g., TLD).
- ☐ In ionization chambers, air is used as the sensitive medium, since it allows a relatively simple electrical means for collection of charges released in the sensitive medium by radiation.



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2.8 CAVITY THEORY

2.8.3 Considerations in the application of cavity theory to ionization chamber calibration and dosimetry protocols

- ☐ In current dosimetry concepts, the ionization chamber is used
 - in a phantom
 - **without** a build-up material.
- ☐ Typical thicknesses of the chamber wall are much thinner than the range of the secondary electrons.
- ☐ Therefore, the proportion of the cavity dose due to electrons generated in the phantom greatly exceeds the dose contribution from the wall.
- ☐ Hence, the **phantom** medium serves as the medium and the wall is treated as a perturbation.



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2.8 CAVITY THEORY

2.8.3 Considerations in the application of cavity theory to ionization chamber calibration and dosimetry protocols

- Taking into account all small perturbations, the dose in the medium is determined with a thin-walled ionization chamber in a high energy photon or electron beam by:

where

$$D_{\text{med}} = \frac{Q}{m} \cdot \left(\frac{W_{\text{gas}}}{e} \right) \cdot S_{\text{med,gas}}^{\text{SA}} \cdot p_{\text{fl}} \cdot p_{\text{dis}} \cdot p_{\text{wall}} \cdot p_{\text{cel}}$$

$S_{\text{med,gas}}^{\text{SA}}$ is the Spencer-Attix stopping power ratio
 W_{gas} is the average energy expended in air per ion pair formed
 p_{fl} is the electron fluence perturbation correction factor
 p_{dis} is the correction factor for displacement of the effective measurement point
 p_{wall} is the wall correction factor
 p_{cel} is the correction factor for the central electrode

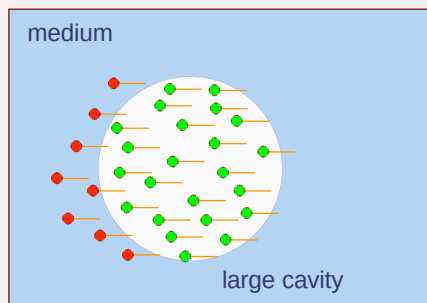


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2.8 CAVITY THEORY

2.8.4 Large cavities in photon beams

- A large cavity is a cavity such that the dose contribution from secondary electrons (= —) originating outside the cavity (= ●) can be ignored when compared with the contribution of electrons created by photon interactions within the cavity (= ●).



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2.8 CAVITY THEORY

2.8.4 Large cavities in photon beams

- For a large cavity the ratio of dose cavity to medium is calculated as the ratio of the collision kerma in the cavity to the medium and is therefore equal to the ratio of the average mass-energy absorption coefficients, cavity to medium:

$$D_{\text{med}} = D_{\text{gas}} \cdot \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_{\text{med,gas}}$$

where the mass-energy absorption coefficients have been averaged over the photon fluence spectra in the medium (numerator) and in the cavity gas (denominator).



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

- **Burlin** extended the Bragg-Gray and Spencer-Attix cavity theories to cavities of **intermediate** dimensions by introducing the large cavity limit to the Spencer-Attix equation using a **weighting technique**.

- This was introduced on a purely phenomenological basis.
- Burlin provided a formalism to calculate the value of the weighting parameter.



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

- Burlin cavity theory can be written in its simplest form as:

$$\frac{D_{\text{gas}}}{D_{\text{med}}} = d \cdot S_{\text{gas,med}} + (1-d) \cdot \left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_{\text{gas,med}}$$

where

d is a parameter related to cavity size approaching unity for small cavities and zero for large ones.

$S_{\text{gas,med}}$ is the mean ratio of the restricted mass stopping powers of the cavity and the medium.

D_{gas} is the absorbed dose in the cavity.

$(\bar{\mu}_{\text{en}} / \rho)_{\text{gas,med}}$ is the mean ratio of the mass-energy absorption coefficients for the cavity and the medium.



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

- Conditions to apply the Burlin theory:

- The surrounding medium and cavity medium are homogeneous.
- A homogeneous photon field exists everywhere throughout the medium and the cavity.
- Charged particle equilibrium exists at all points in the medium and the cavity that are further than the maximum electron range from the cavity boundary.
- The equilibrium spectra of secondary electrons generated in the medium and the cavity are the same.



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

❑ How to get the the weighting parameter d in this theory?

Burlin provided the following method:

- d is expressed as the average value of the electron fluence reduction in the medium.
- Consistent with experiments with β -sources he proposed that on average the electron fluence in the medium Φ_{med}^e decays exponentially.
- The value of the weighting parameter d in conjunction with the stopping power ratio can be calculated as:

$$d = \frac{\int_0^L \Phi_{\text{med}}^e e^{-\beta \ell} d\ell}{\int_0^L \Phi_{\text{med}}^e d\ell} = \frac{1 - e^{-\beta L}}{\beta L}$$



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

- ❑ In this theory, β is an effective electron fluence attenuation coefficient that quantifies the reduction in particle fluence from its initial medium fluence value through a cavity of average length L .
- ❑ For convex cavities and isotropic electron fluence distributions, L can be calculated as $4V/S$ where V is the cavity volume and S its surface area.
- ❑ Burlin described the build-up of the electron fluence Φ inside the cavity using a similar, complementary equation:

$$1 - d = \frac{\int_0^L \Phi_{\text{gas}}^e \cdot (1 - e^{-\beta \ell}) d\ell}{\int_0^L \Phi_{\text{gas}}^e d\ell} = \frac{\beta L - 1 + e^{-\beta L}}{\beta L}$$



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2.8 CAVITY THEORY

2.8.5 Burlin cavity theory for photon beams

- ❑ Burlin's theory is consistent with the fundamental constraint of cavity theory that, the weighting factors of both terms add up to unity (*i.e.*, d and $(1-d)$).
- ❑ It had relative success in calculating ratios of absorbed dose for some types of intermediate cavities.
- ❑ More generally, however, Monte Carlo calculations show that, when studying ratios of directly calculated absorbed doses in the cavity to absorbed dose in the medium as a function of cavity size, the weighting method is too simplistic and additional terms are necessary to calculate dose ratios for intermediate cavity sizes.
- ❑ For these and other reasons, the Burlin cavity theory is no longer used in practice.



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2.8 CAVITY THEORY

2.8.6 Stopping power ratios

- ❑ For high energy photons and electrons, the stopping power ratio, as defined by:

$$S_{\text{med1,med2}} = \left(\frac{\bar{S}}{\rho} \right)_{\text{med1}} / \left(\frac{\bar{S}}{\rho} \right)_{\text{med2}}$$

is the important link to perform an absolute measurement of absorbed dose in a medium med1 with a dosimeter made of a medium med2.



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2.8 CAVITY THEORY

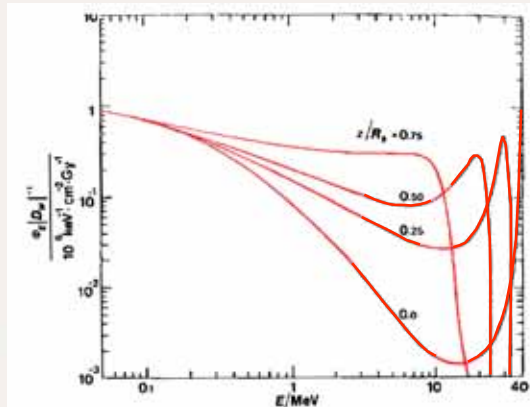
2.8.6 Stopping power ratios

- It is also in particular relevant in performing accurate **relative** measurements of absorbed dose in a phantom where the energy of the electrons changes significantly.

Example from ICRU 35:

Energy spectrum of electrons with of 40 MeV initial energy in a water phantom at **different depth z** (expressed by z/R_p)

Values were normalized to that at surface for 40 MeV .

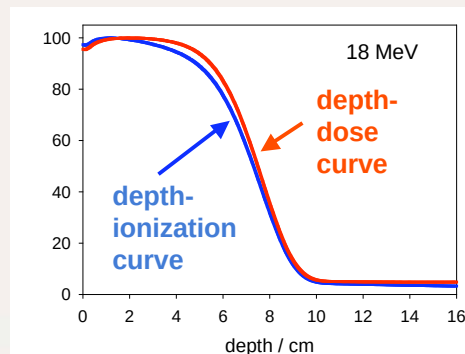


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2.8 CAVITY THEORY

2.8.6 Stopping power ratios

- The measurement of the relative dose in air changes with depth with an ionization chambers always provide a **depth-ionization** curve.
- The **depth-ionization** curve of electrons differs from the **depth-dose** curve by the water-to-air stopping power ratio.



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2.8 CAVITY THEORY

2.8.6 Stopping power ratios

- ❑ As shown in the previous slides, the Spencer-Attix ratio of restricted collision stopping powers are required for this.
- ❑ However, due to the energy distribution of electrons at each point along the depths of measurement, one **CANNOT** use directly the stopping power ratios for monoenergetic electrons.
- ❑ Instead of, one must determine them for the energy distribution of electrons at realistic linac beams.



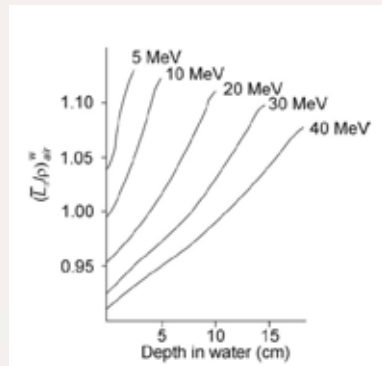
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2.8 CAVITY THEORY

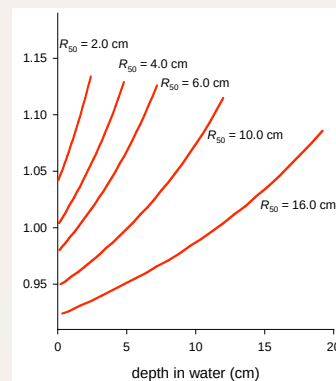
2.8.6 Stopping power ratios

Restricted stopping power ratios ($\Delta = 10$ keV) of water to air for electron beams as a function of depth in water (from TRS 398).

For mono-energetic electrons



For realistic linac beams



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2.8 CAVITY THEORY

2.8.6 Stopping power ratios

Stopping power ratios required for photon beams

- ❑ In photon beams, average restricted stopping power ratios of water to air do **NOT** vary significantly as a function of depth.
- ❑ Exception: at or near the surface
- ❑ Stopping power ratios (with $\Delta = 10$ keV) under full build-up conditions are given in the table as a function of the beam quality index $\text{TPR}_{20,10}$.

Photon Spectrum	$\text{TPR}_{20,10}$ (from TRS 398)	$\frac{-\Delta}{L_{w,a}}$
^{60}Co	0.519	1.134
4 MV	0.581	1.131
6 MV	0.626	1.127
8 MV	0.667	1.121
10 MV	0.688	1.117
15 MV	0.731	1.106
20 MV	0.760	1.096
25 MV	0.768	1.093
35 MV	0.789	1.084



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