Chapter 3. Fundamentals of Dosimetry

Slide series of 44 slides based on the Chapter authored by E. Yoshimura
of the IAEA publication (ISBN 978-92-0-131010-1):

Diagnostic Radiology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize students with quantities and units used for describing the interaction of ionizing radiation with matter

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IAEA
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3.1. INTRODUCTION

Subject of dosimetry: determination of the energy imparted by radiation to matter. This energy is responsible for the effects that radiation causes in matter, for instance:

- a rise in temperature
- chemical or physical changes in the material properties
- biological modifications

Several of the changes produced in matter by radiation are proportional to absorbed dose, giving rise to the possibility of using the material as the sensitive part of a dosimeter

There are simple relations between dosimetric and field description quantities

3.2. QUANTITIES AND UNITS USED FOR DESCRIBING THE INTERACTION OF IONIZING RADIATION WITH MATTER

In diagnostic radiology, the radiation protection of staff and patients is the most important application of the dosimetric quantities:

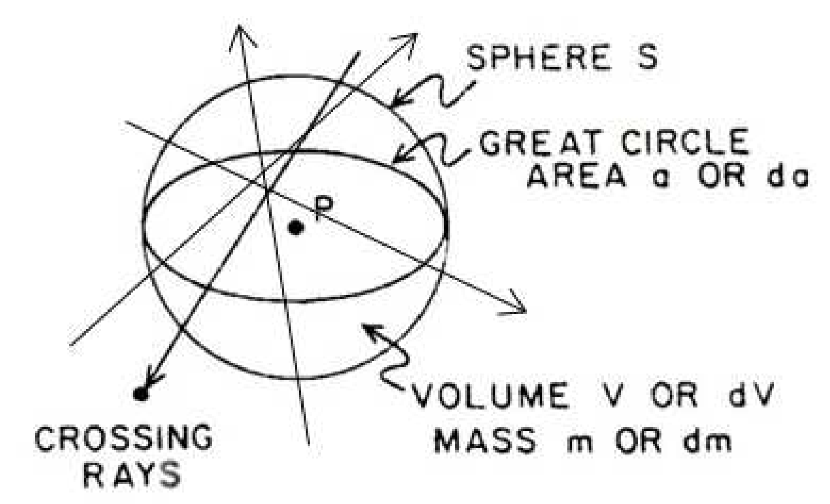
- **exposure**, or more precisely exposure dose, is related to the ability of a photon beam to ionize the air
- **kerma**, a more general quantity that is recommended for dosimeter calibration purposes
- **absorbed dose** is the quantity that better indicates the effects of radiation in materials or on human beings, and, accordingly, all the protection related quantities are based on it

3.2. QUANTITIES AND UNITS USED FOR DESCRIBING THE INTERACTION OF IONIZING RADIATION WITH MATTER

3.2.1. Radiation fields: fluence

Definition of fluence Φ (m^{-2})

A radiation field at a point P can be quantified by the physical non-stochastic quantity, fluence Φ, given by:



$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

$\mathrm{d}N$ is the differential of the expectation value of the number of particles (photons, or massive particles) striking an infinitesimal sphere with a great- circle area $\mathrm{d}a$ surrounding point P

Particles included in Φ may have any direction, but correspond to **one type of radiation**, so that **photons** and **electrons** are counted separately contributing to the **photon fluence** and the **electron fluence** respectively

3.2. QUANTITIES AND UNITS USED FOR DESCRIBING THE INTERACTION OF IONIZING RADIATION WITH MATTER

3.2.1. Radiation fields: energy fluence

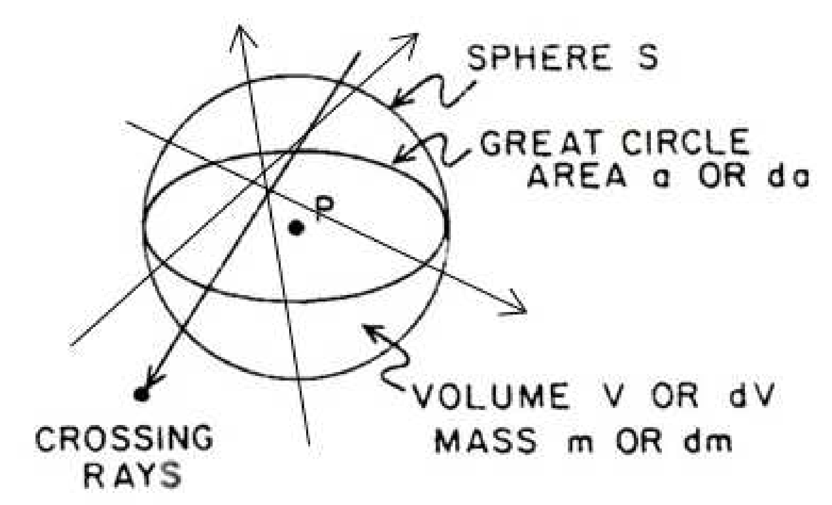
Definition of energy fluence Ψ (J·m^{-2})

$$\Psi = \frac{\mathrm{d}R}{\mathrm{d}a}$$

is the sum the radiant energy R of **each particle** that strikes the infinitesimal sphere *S*

$\mathrm{d}R$ is the differential of the radiant energy R:

- **kinetic energy of massive particles or**
- **energy of photons**



If the radiation field is composed of particles, each with the same energy , E, the energy fluence is related to the fluence Φ :

$$\Psi = E\ \Phi$$

3.2. QUANTITIES AND UNITS

3.2.2. Energy transferred, net energy transferred, energy imparted

When an X ray photon interacts with matter, part of its energy is transferred in various interaction events

Energy transferred (ε_{tr}) is given by the sum of all the initial kinetic energies of charged ionizing particles liberated by the uncharged particles in the volume V

As the liberated charged particles interact with matter, part of initial kinetic energy can be irradiated as photons

Net energy transferred (ε_{tr}^{net}) is given by ε_{tr} minus the energy carried by photons

Energy imparted (ε) is defined for any radiation (charged or uncharged) and is related to the part of the radiant energy that can produce effects within an irradiated volume

3.2. QUANTITIES AND UNITS

3.2.2.1. Energy transferred ε_{tr}

For photons in the diagnostic energy range, ε_{tr} , is the sum of the kinetic energies of electrons at the moment they are set free in an incoherent scattering or photoelectric interaction in the volume *V*

For photons with energies above the pair production threshold of 1.022 MeV, kinetic energy may also be transferred to positrons

As the liberated charged particles interact with matter, part of their initial kinetic energy can be irradiated as photons:

- **Bremsstrahlung radiation**
- **In-flight annihilation of positrons**

3.2. QUANTITIES AND UNITS

3.2.2.1. Net energy transferred ε_{tr}^{net}

$$\varepsilon_{tr}^{net} = \varepsilon_{tr} - \sum h\nu_{brem} - \sum T_{ann}$$

ε_{tr}^{net} : net energy transferred

ε_{tr} : energy transferred

$\sum h\nu_{brem}$: energies of the Bremsstrahlung photons

$\sum T_{ann}$: energies of the annihilation photons

For *energy transferred* and *net energy transferred,* the volume *V* is the volume where the initial uncharged particles interact. It does not matter if the range of the charged particles is restricted to *V* or not, their initial kinetic energies are all included in ε_{tr}, and all the Bremsstrahlung emissions and excess of energy of the annihilation photons are excluded from ε_{tr}^{net}

For photons, in the diagnostic energy range, incident on low Z materials

$$\varepsilon_{tr}^{net} = \varepsilon_{tr}$$

3.2.2.2. Energy imparted ε

Energy imparted ε:

is defined for charged or uncharged ionizing radiation and is related to the deposition of energy in matter. It is that part of the radiant energy that can produce effects within irradiated volume V

$$\varepsilon = R_{in} - R_{out} + E_{m\rightarrow R} - E_{R\rightarrow m}$$

R_{in} : radiant energy that enters the volume

R_{out} : radiant energy that leaves the volume

$E_{m\rightarrow R}$: change in energy when the rest mass of a particle is converted to radiant energy ($m\rightarrow R$)

$E_{R\rightarrow m}$: change in energy when the energy of a photon is converted to the mass of particles ($R\rightarrow m$) inside the volume V

For photons in the diagnostic energy range:

$$\varepsilon = R_{in} - R_{out}$$

3.2. QUANTITIES AND UNITS

3.2.3. Kerma and collision kerma

Kerma K (Gy) is a non-stochastic quantity, related to the energy transferred from uncharged particles to matter

Kerma is the acronym for Kinetic Energy Released per unit Mass

$$K = \frac{\mathrm{d}\varepsilon_{tr}}{\mathrm{d}m}$$

Kerma is measured in gray (Gy), 1 Gy = 1 J/kg

$\mathrm{d}\varepsilon_{tr}$ **: expectation value of the energy transferred from indirectly ionizing radiation to charged particles in the elemental volume $\mathrm{d}V$ of mass $\mathrm{d}m$**

Kerma:

- **may be defined in any material**
- **is defined for indirectly ionizing radiation (photons and neutrons)**
- **is the kinetic energy transferred to the secondary particles that is not necessarily spent in the volume ($\mathrm{d}V$) where they were liberated**

3.2. QUANTITIES AND UNITS

3.2.3.1. Components of kerma

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

$$K_{col} = \frac{\mathrm{d}\varepsilon_{tr}^{net}}{\mathrm{d}m}$$

Collision kerma (K_{col}) is related to the part of the kinetic energy of the secondary charged particles which is spent in **collisions**, resulting in ionization and excitation of atoms in matter. It is the expectation value of the net energy transferred

$$K_{rad}$$

Radiative kerma (K_{rad}) is related to the portion of the initial kinetic energy of the secondary charged particles which is converted into **photon energy**. It is simpler to define radiative kerma as the difference: $K_{rad} = K - K_{col}$

3.2. QUANTITIES AND UNITS

3.2.4.1. Kerma and fluence for photons

$$K = \Phi \; h\nu \left(\frac{\mu_{tr}}{\rho}\right) = \left(\frac{\mu_{tr}}{\rho}\right) \Psi$$

Kerma K at a point P in space where there is a fluence Φ of monoenergetic photons with energy $h\nu$

$$K_{col} = \Phi \; h\nu \left(\frac{\mu_{en}}{\rho}\right) = \left(\frac{\mu_{en}}{\rho}\right) \Psi$$

Collision kerma K_{col}

$\left(\frac{\mu_{tr}}{\rho}\right)$ **: mass energy transfer coefficient**

Ψ **: energy fluence**

$\left(\frac{\mu_{en}}{\rho}\right)$ **: mass energy absorption coefficient**

Relationship between collision and total kerma $K_{col} = K(1-g)$

g gives the energy fraction lost to radiative processes. For the energies used in diagnostic radiology, g may be taken as zero

3.2. QUANTITIES AND UNITS

3.2.4.1. Kerma and fluence for photons

If the photon beam has a spectrum of energies:

$$K = \Phi \; h\nu \left(\frac{\mu_{tr}}{\rho}\right) = \left(\frac{\mu_{tr}}{\rho}\right) \Psi$$ **Kerma *K***

$$K_{col} = \Phi \; h\nu \left(\frac{\mu_{en}}{\rho}\right) = \left(\frac{\mu_{en}}{\rho}\right) \Psi$$ **Collision kerma K_{col}**

both equations may be generalized through a summation or integration over the range of energies of the discrete or continuous spectrum

3.2. QUANTITIES AND UNITS

3.2.4.2. Kerma and Exposure

Exposure X (C·kg^{-1}) is a quantity related to collision kerma when X or gamma ray photons interact with air

$$X = \frac{\mathrm{d}Q}{\mathrm{d}m}$$

$\mathrm{d}Q$ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated by photons in air of mass $\mathrm{d}m$ are stopped in air

The energy spent to produce $\mathrm{d}Q$ corresponds to the expectation value of the net energy transferred to charged particles in air ($\mathrm{d}\varepsilon_{tr}^{net}$)

The unit of exposure in SI is:
coulomb per kilogram (C·kg^{-1}), even though an old non-SI unit (roentgen – R) is still in use

The conversion from R to SI is:

$$1\ \mathrm{R} = 2.580 \times 10^{-4}\ \mathrm{C{\cdot}kg^{-1}}$$

Relationship between air collision kerma and exposure X

The relationship between $\mathrm{d}Q$ and $\mathrm{d}\varepsilon_{tr}^{net}$ can be expressed in terms of the measurable quantity, the mean energy $\overline{W}_{air}$ spent in air to form an ion pair

$$\overline{W}_{air} = \frac{\sum \text{kinetic energies of electrons spent in ionization and excitation}}{\sum \text{ion pairs produced by the secondary electrons in air}}$$

$$\overline{W}_{air} = 33.97\,\mathrm{eV/ion\ pair} = 33.97\,\mathrm{J\cdot C^{-1}}$$

$$(K_{col})_{air} = \overline{W}_{air}\,X = 33.97\,X \quad \text{(SI)}$$

or

$$(K_{col})_{air} = 0.876\times10^{-2}\,X \quad (X \text{ in R, } K \text{ in Gy})$$

3.2. QUANTITIES AND UNITS

3.2.5. Absorbed dose

Absorbed dose *D* (Gy) is a physical non-stochastic quantity

$$D = \frac{d\varepsilon}{dm}$$

$d\varepsilon$ is the expectation value of the energy imparted by any ionizing radiation to the matter of mass dm. Absorbed dose is expressed in the same unit as kerma, joule per kilogram ($J \cdot kg^{-1}$) in SI which receives the special name gray, Gy

When a large volume is irradiated, energy can be imparted to the matter in a specific volume by radiation that comes from other regions, sometimes very far from the volume of interest

The knowledge of the radiation fluence in the volume of interest, including scattered radiation, is necessary for the calculation of absorbed dose

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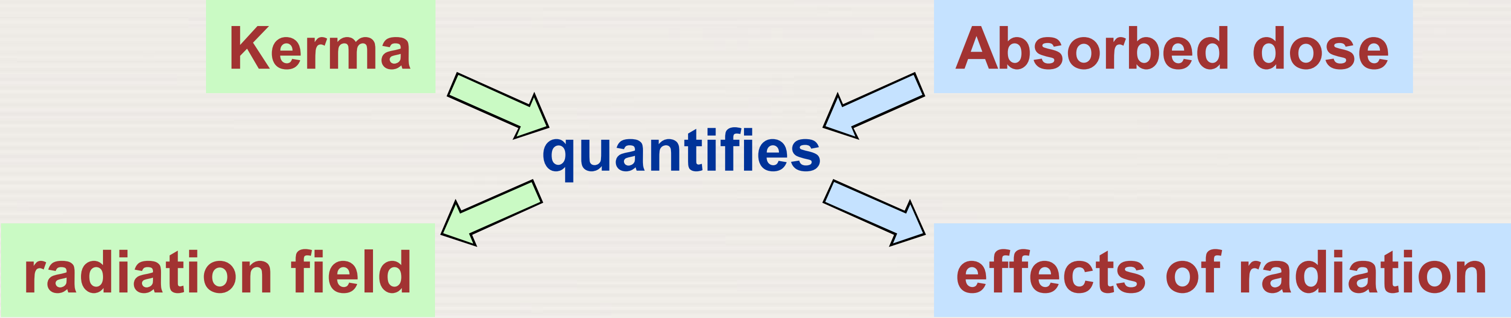
3.2. QUANTITIES AND UNITS

3.2.6. Kerma and absorbed dose

Kerma and **absorbed dose** are related to the quantification of the interaction of radiation with the matter



Kerma

Absorbed dose

quantifies

radiation field

effects of radiation

Volume of interest V

Kerma: V is the place where energy is transferred from uncharged to charged particles

Absorbed dose: V is the place where the kinetic energy of charged particles is spent

Charged particles entering V **contribute to** **absorbed dose**, **but not to** **Kerma**

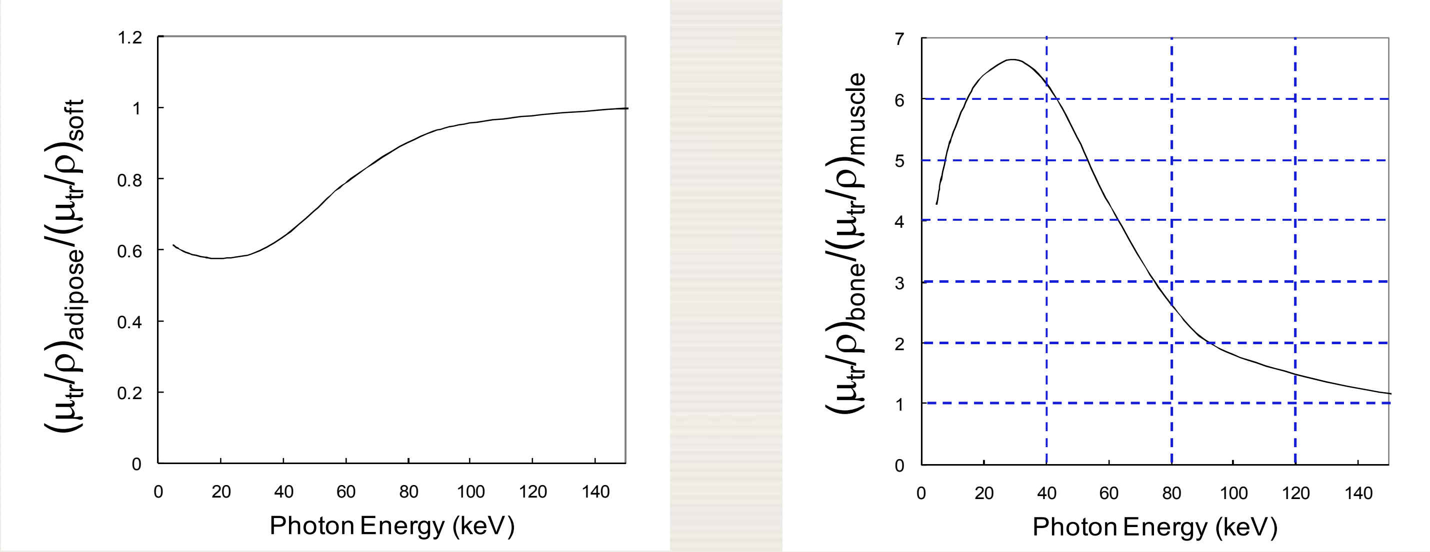
Charged particles liberated by a photon in V may leave it, carrying away part of their kinetic energy: this energy is **included in** **Kerma**, but **not in** **absorbed dose**

3.2. QUANTITIES AND UNITS

3.2.6. Kerma and absorbed dose

The largest differences between absorbed dose and kerma appear at interfaces between different materials, as there are differences in ionization density and in scattering properties of the materials

The changes in kerma at the boundaries are stepwise (scaled by the values of the mass energy transfer coefficient), but the changes in absorbed dose are gradual, extending to a region with dimensions comparable to the secondary particle ranges



Ratio of mass energy transfer coefficients for some tissue pairs

3.2. QUANTITIES AND UNITS

3.2.6. Kerma and absorbed dose

Electron energy (keV)	Range in water[a]	Range in compact bone[a]
10	2.52 µm	1.49 µm
20	8.57 µm	5.05 µm
50	43.2 µm	25.3 µm
80	97.7 µm	57.1 µm
100	0.143 mm	0.084 mm
150	0.282 mm	0.164 mm
1000	0.437 cm	0.255 cm

Range of electrons in water and in bone

[a] values of CSDA range obtained with ESTAR program, available at (http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html)

The ranges of electrons set in motion by photons used in diagnostic radiology are small in biological tissues, being less than 1 mm for most of the energies. This indicates that the changes in absorbed dose at the interface between two tissues in the body are limited to small regions

3.2. QUANTITIES AND UNITS

3.2.7. Diagnostic dosimeters

Dosimeters are devices used to determine absorbed dose or kerma, or their time rates, based on the evaluation of a detector physical property, which is dose-dependent

A dosimeter is composed of:

- the detector and
- other components which convert the detector signal to the absorbed dose or kerma value

The measurements necessary for dosimetry include:

- X ray tube output determination
- patient dosimetry through the determination of incident or entrance air kerma
- kerma-area product (KAP) or internal organ doses
- control of doses to staff, through area and individual monitoring

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

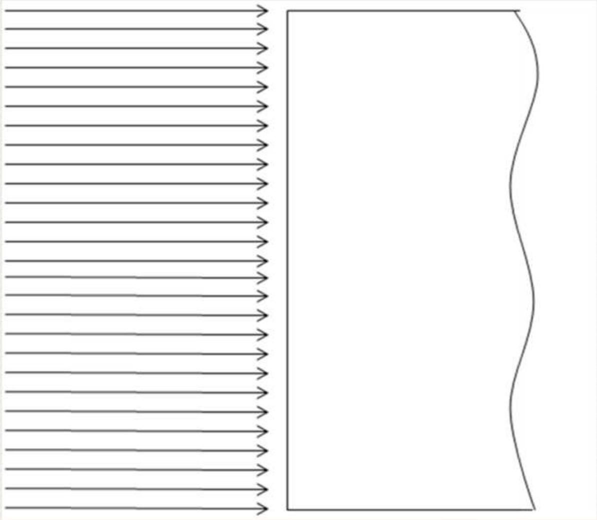
When a beam of uncharged ionizing particles irradiates an homogeneous material, the ionizing radiation field is transformed to a mixture of:

- the incident beam (attenuated by the material)
- the scattered radiation produced by the interaction of the incident beam in the material
- Bremsstrahlung radiation
- charged particles: the secondary particles liberated by the incident radiation in the material and the electrons set in motion by the secondary particles

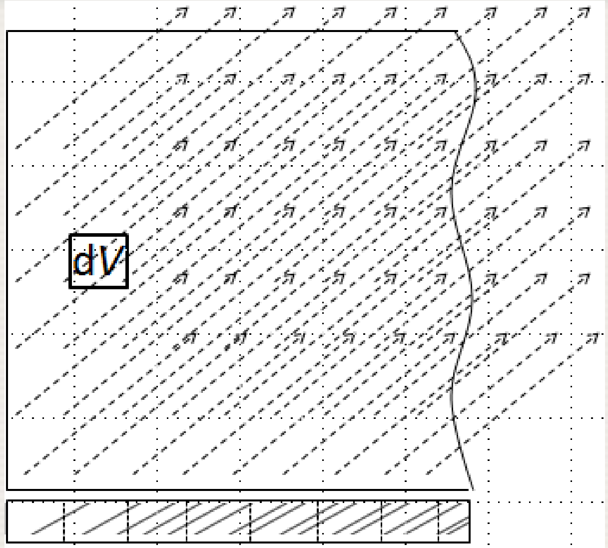
The accurate description of the components of the radiation field in a volume where absorbed dose or kerma are to be determined cannot be done with analytical methods. This can be done with numerical methods (like Monte Carlo simulation) or, experimentally when there is equilibrium of charged particles in the volume

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.1. Charged particle equilibrium (CPE)



a) Geometry of a material irradiated from the left with a monoenergetic beam of photons with $E = h\nu$



b) The tracks of the charged particles liberated in the material

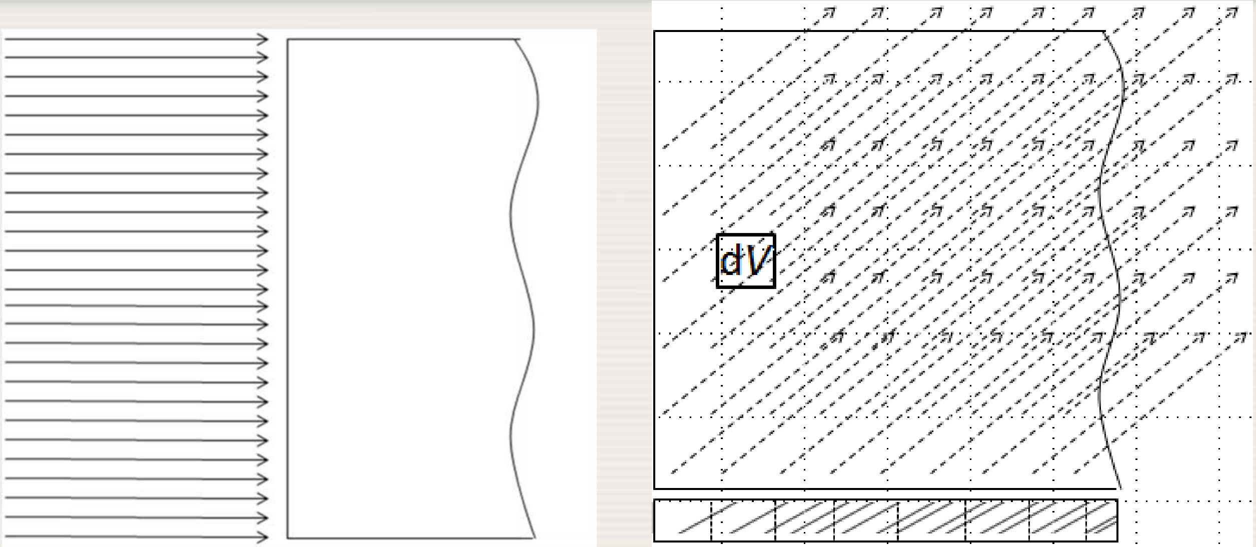
The bottom section of the figure shows the path lengths of the charged particles as the position of the volume $\mathrm{d}V$ moves in a direction parallel to the incoming beam

Assumption: all electrons liberated have

- **the same direction**
- **the same energy**
- **straight track**

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.1. Charged particle equilibrium (CPE)



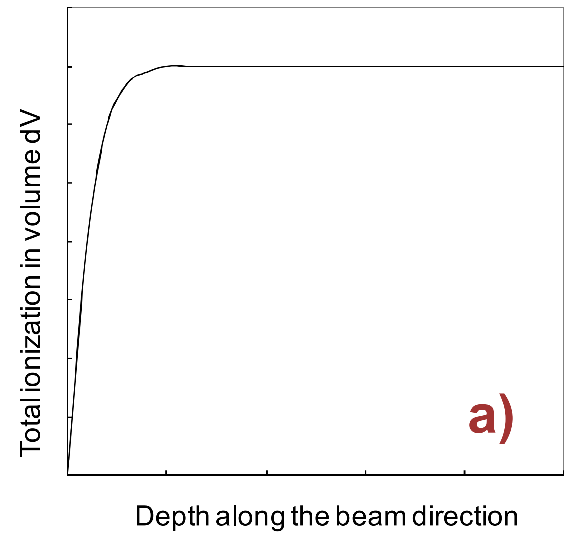
The number of electron tracks which crosses $\mathrm{d}V$ is small near the surface of the material, but increases as the volume moves to a greater depth, because more electrons are liberated by photon interactions

As the electron paths have finite lengths (ranges) in the material, the number of tracks reaches a maximum at a particular position of $\mathrm{d}V$, and eventually begins to decrease, as the beam is attenuated for greater depths

The total path length of charged particles in each volume represents the number of ionizations that occurs in the volume

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

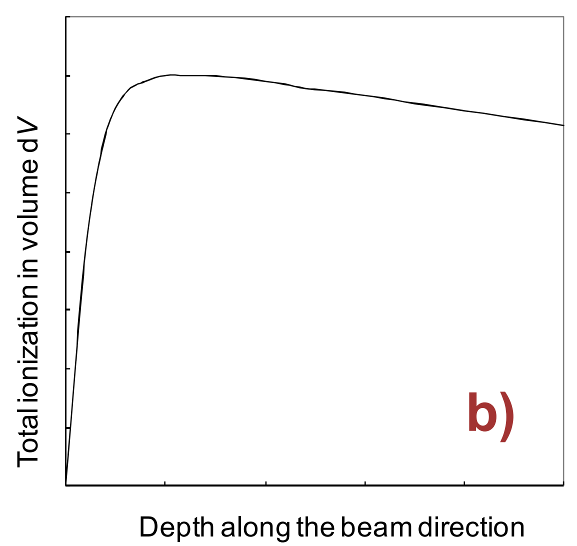
3.3.1. Charged particle equilibrium (CPE)



Total ionization inside a volume dV as a function of the depth of the volume in the material, with the assumptions:

a) the photon fluence is constant

b) the photon beam is attenuated as it enters the material

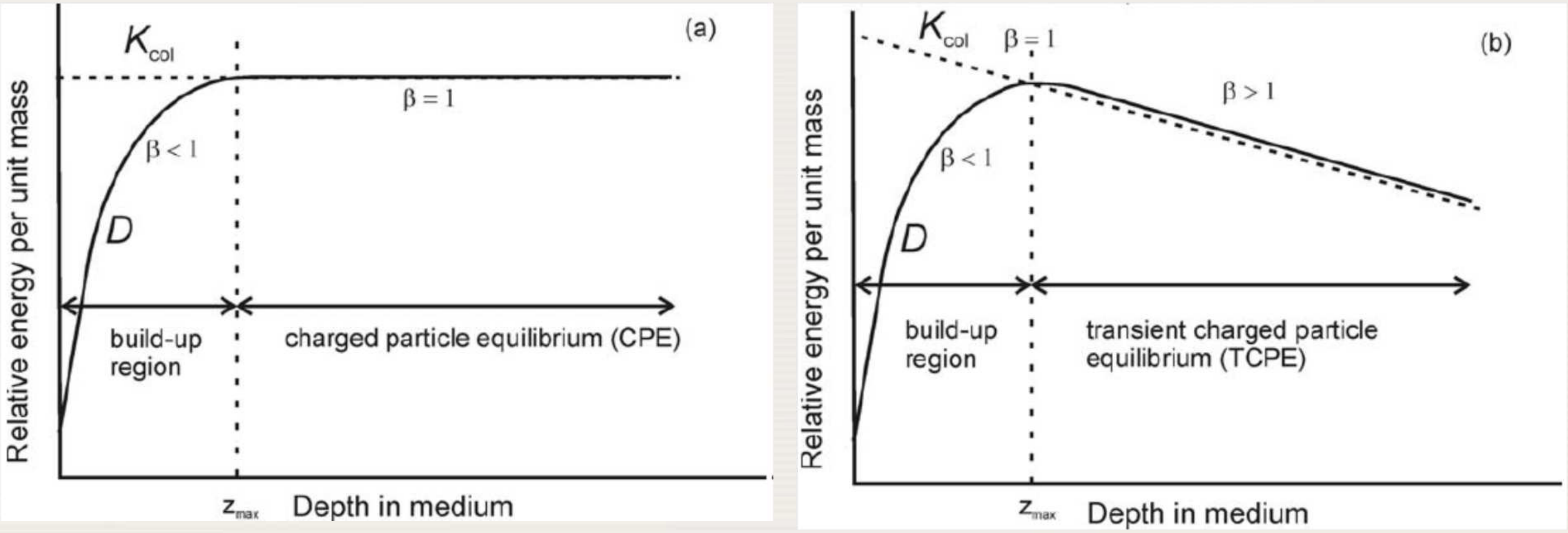


The state of constant ionization is named charged particle equilibrium (CPE), because in this situation the charged particles which are liberated in the volume dV and leave the volume are balanced, in number and energy, by particles which were liberated elsewhere, and that enter volume dV

The expectation value of the total ionization in volume dV increases initially but then decreases slowly with increasing depth in the medium, when attenuation of photon beam is considered. The state, at depths beyond the maximum of ionization, is called transient charged particle equilibrium (TCPE)

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.2. Relationships between absorbed dose, collision kerma, and exposure under CPE



Collision kerma and absorbed dose as a function of depth in a medium, irradiated by a high-energy photon beam

Ref. (from IAEA – Syllabus on radiation therapy)

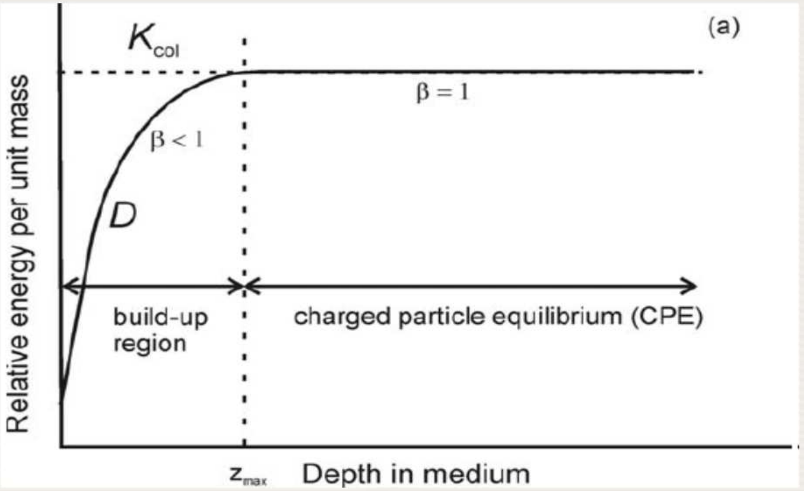
Kerma and collision kerma at the entrance of the material are readily obtained by equations

$$K = \Phi\, h\nu \left(\frac{\mu_{tr}}{\rho}\right) = \left(\frac{\mu_{tr}}{\rho}\right)\Psi$$

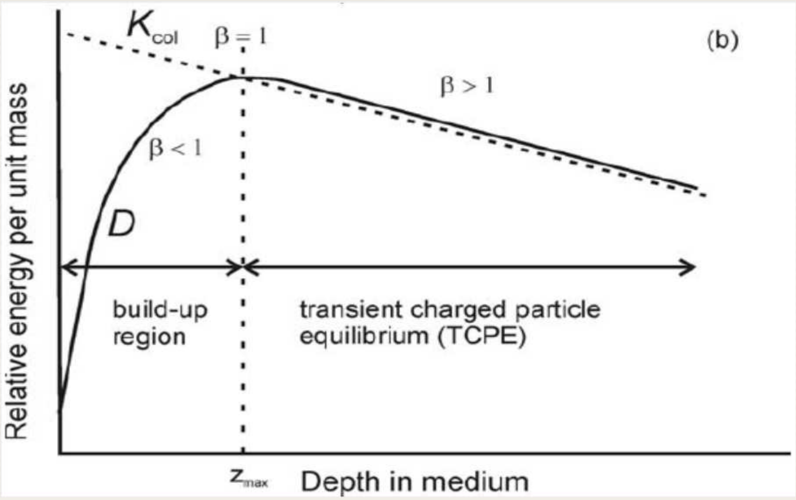
$$K_{col} = \Phi\, h\nu \left(\frac{\mu_{en}}{\rho}\right) = \left(\frac{\mu_{en}}{\rho}\right)\Psi$$

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.2. Relationships between absorbed dose, collision kerma, and exposure under CPE



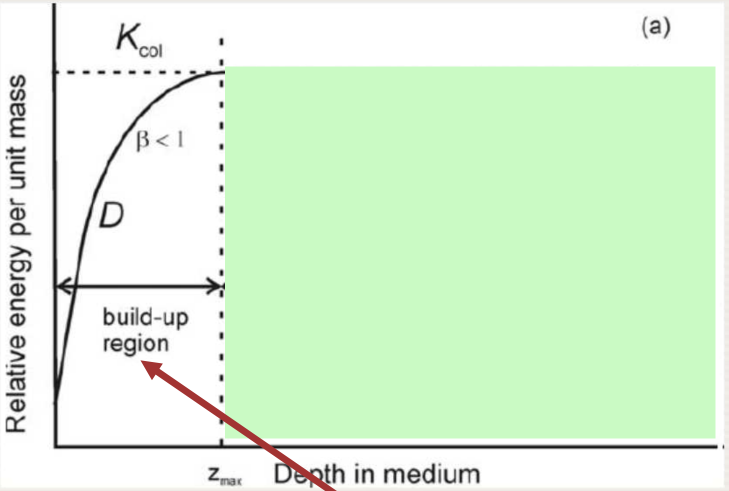
When the number of interactions is so small that the fluence may be considered constant inside the medium, the variation of K_{col} with depth will be in accordance with Fig. a

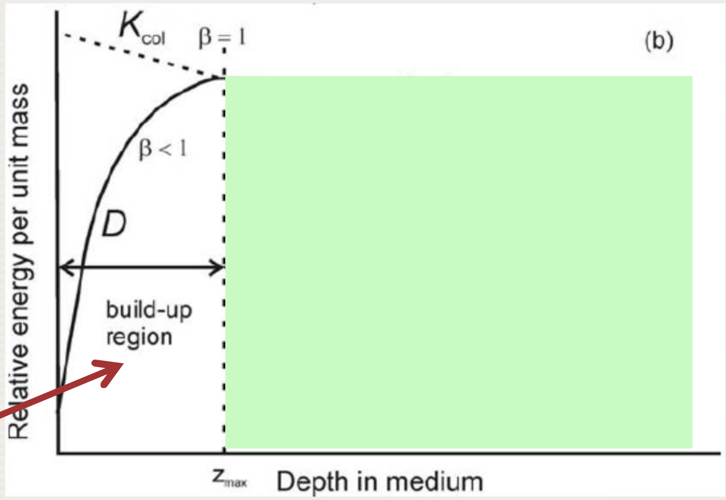


Usually, however, it is considered that the fluence decreases exponentially with depth in the material, with similar behaviour for K_{col} as shown in Fig. b

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.2. Relationships between absorbed dose, collision kerma, and exposure under CPE



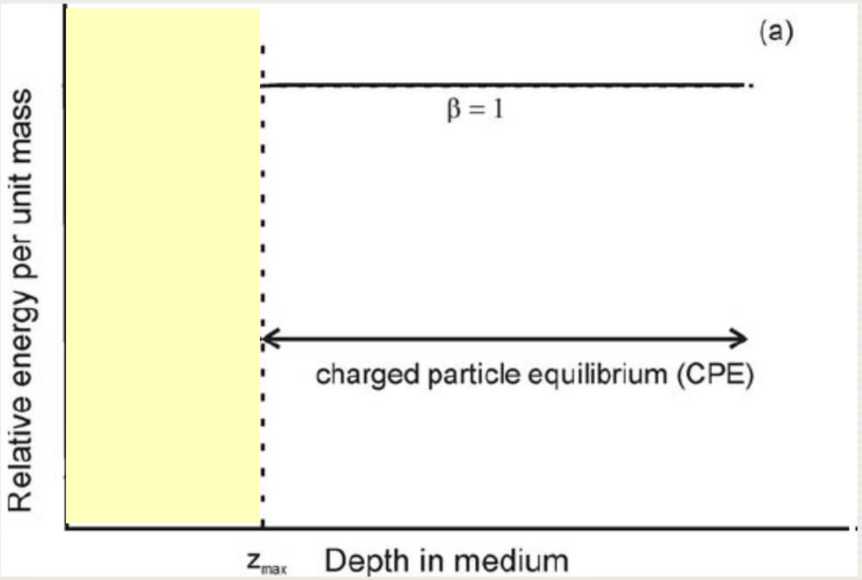


There is a build-up region for the dose, at small depths in the medium. The build-up region has dimensions (z_{max}) similar to the range of the charged particles in the medium

Absorbed dose, *D*, depends on the deposition of energy by charged particles. It is smaller at the surface of the material than inside it

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.2. Relationships between absorbed dose, collision kerma, and exposure under CPE



Assumption: changes in photon fluence are small, and the volume of interest has small dimensions compared to the electron range

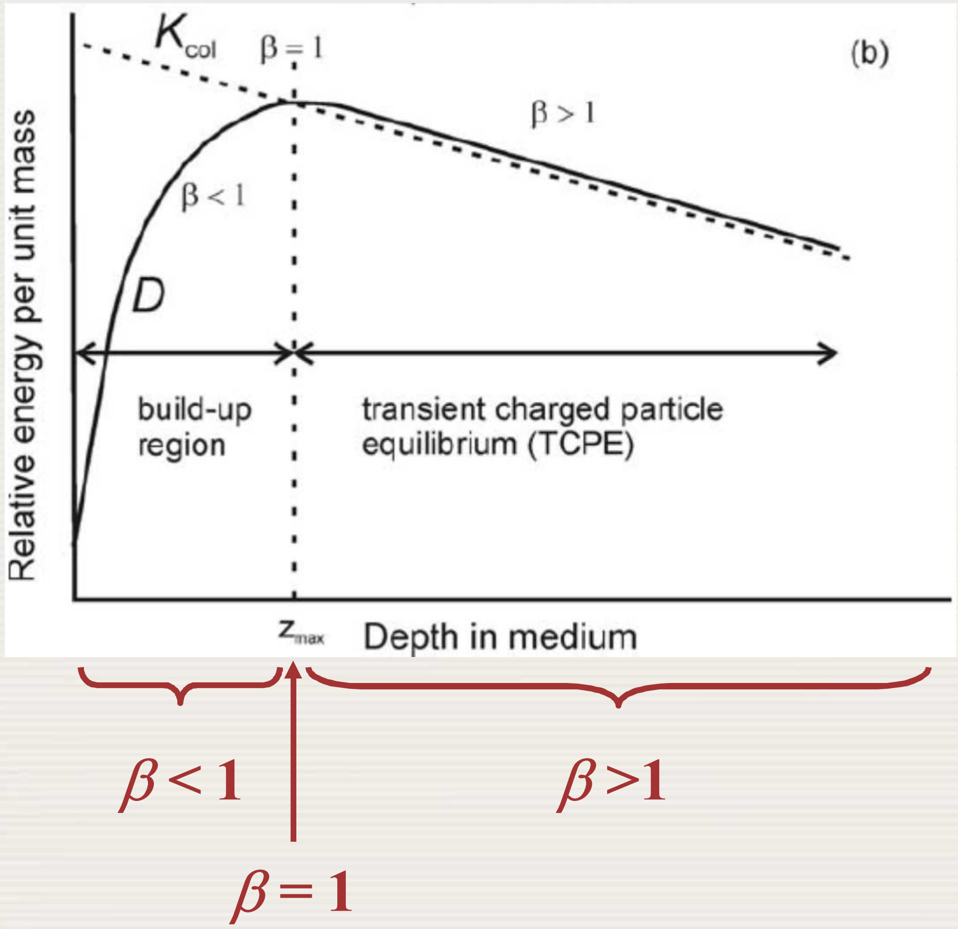
Beyond the build-up region the relation between absorbed dose and collision kerma is:

$$D \overset{CPE}{=} K_{col} = \Phi \, h\nu \left(\frac{\mu_{en}}{\rho}\right)$$

There is a coincidence of absorbed dose and the collision kerma, as true charged particle equilibrium is achieved

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.2. Relationships between absorbed dose, collision kerma, and exposure under CPE



When the attenuation of the photon beam is not negligible, beyond the maximum, the absorbed dose is larger than the collision kerma, as the energy imparted is due to charges liberated by photon fluences slightly larger than the fluence in the volume of interest. Because there is practically constant ratio between these quantities it is usual to write:

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

$\beta \approx 1$ can be used for diagnostic radiology and low *Z* materials

3.3. CHARGED PARTICLE EQUILIBRIUM IN DOSIMETRY

3.3.3. Conditions that enable CPE or cause its failure

The necessary and sufficient conditions that guarantee the CPE are:

- **the medium is homogeneous in both atomic composition and mass density** (avoids changes in the charged particle distribution in the material)
- **the photon field is homogeneous in the volume considered** (requires that the dimensions of the volume of interest are not very large, compared to the mean free path of the photons)

Some examples of practical situations where there is a failure in the conditions, so that the CPE cannot be accomplished are:

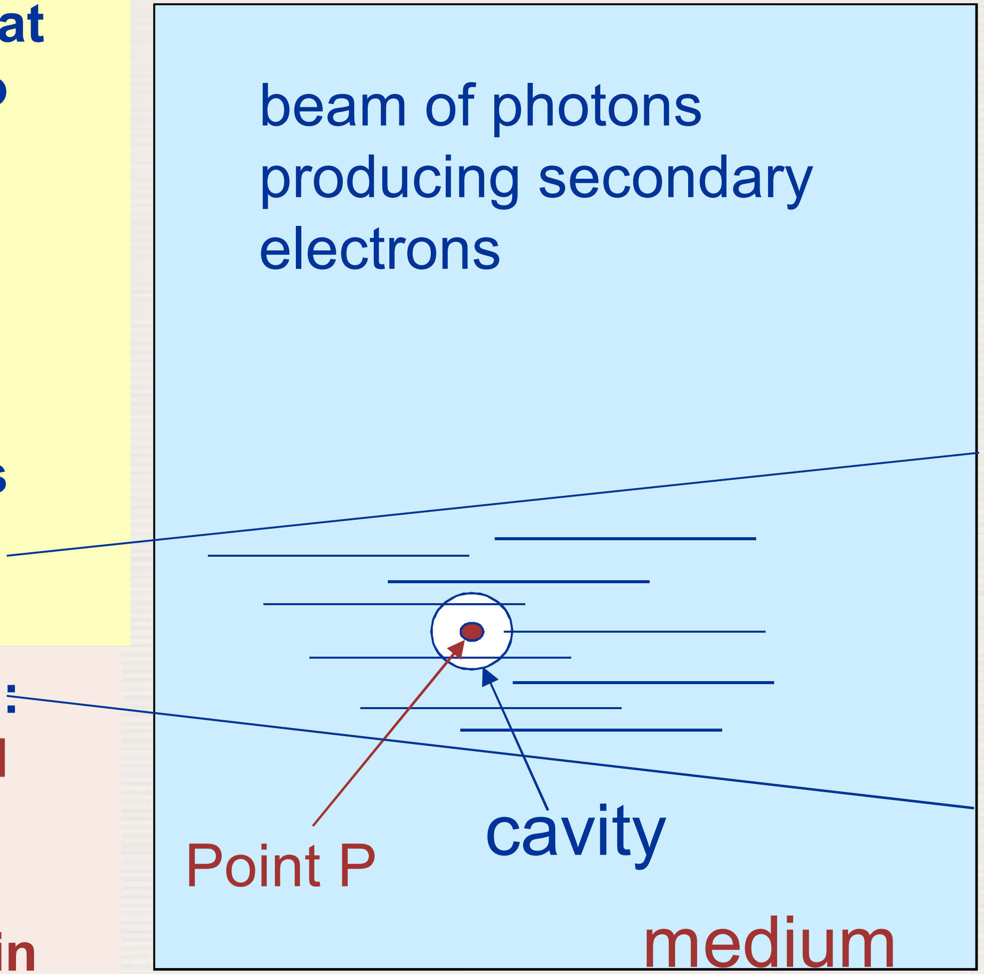
- **large beam divergence, as with irradiations close to the radiation source**
- **proximity of boundaries of the material and any other medium**

3.4. 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
- the sensitive volume of the dosimeter is in general not made of the same material as the medium

The main interests of the cavity theory are:

- to study the modifications of charge and radiation distribution produced in the medium by the cavity
- to establish relations between the dose in the sensitive volume of the dosimeter and the dose in the medium

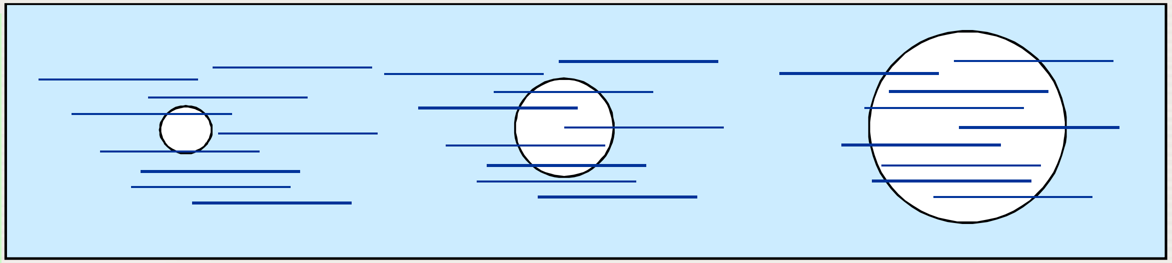


Adapted from IAEA – Syllabus on radiation therapy.
Slide prepared by G.H.Hartmann

3.4. CAVITY THEORY

3.4.1. Bragg-Gray cavity theory

A cavity can be of small, intermediate or large size compared to the range of the charged particles in the cavity



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The Bragg-Gray theory deals with small cavities

W. H. Bragg began the development of the theory, in 1910, but it was L. H. Gray, during his PhD work, co-supervised by Bragg, who formalized the theory

3.4. CAVITY THEORY

3.4.1. Bragg-Gray cavity theory

The main assumptions of this theory are:

- the cavity dimensions are so small compared to the range of charged particles within it so that the fluence of charged particles inside the cavity is not perturbed by the presence of the cavity
- there are no interactions of uncharged particles in the cavity so that the absorbed dose deposited in the cavity is due to the charged particles that cross the cavity

Under these conditions:

$$\frac{D_w}{D_g} = \frac{\int_{T_{\min}}^{T_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}T}\right)_w \left(\frac{\mathrm{d}T}{\rho \mathrm{d}x}\right)_{c,w} \mathrm{d}T}{\int_{T_{\min}}^{T_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}T}\right)_w \left(\frac{\mathrm{d}T}{\rho \mathrm{d}x}\right)_{c,g} \mathrm{d}T} = \bar{\bar{S}}_g^{w}$$

D_w is the absorbed dose in the medium w

D_g is the absorbed dose in the cavity g

$\left(\frac{\mathrm{d}\Phi}{\mathrm{d}T}\right)_w$ is the fluence energy distribution of the electrons in the medium

The symbol $\bar{\bar{S}}_g^{w}$ has the double bar to indicate that this ratio of average stopping-powers considers both the average over the photon-generated electron spectrum and the changes in this spectrum due to the continuous loss of kinetic energy in the materials.

3.4. CAVITY THEORY

3.4.2. The Fano Theorem

The conditions required by the Bragg-Gray theory are better accomplished if the composition (atomic number) of the cavity is similar to that of the medium

This was observed in experiments with cavities filled with different gas compositions, and in 1954, U. Fano proved the theorem:

In a medium of given composition exposed to a uniform field of primary radiation, the field of secondary radiation is also uniform and independent of the density of the medium, as well as of the density variations from point to point

The Fano theorem is important because it relaxes the requirements on the size of the cavity, which are very hard to meet, for instance, when the photon beam is of low energy

The theorem is valid only for infinite media and in conditions where the stopping-power is independent of density

3.4. CAVITY THEORY

3.4.3. Other cavity sizes

The dose to material w, D_w , that surrounds the cavity and the dose to the medium m, D_m , where the cavity is immersed are related by the expression:

$$\frac{D_m}{D_w} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_m}{\left(\frac{\mu_{en}}{\rho}\right)_w}$$

Three conditions are implicit:

- there is CPE in material w and in medium m
- the photon beam is monoenergetic
- the photon fluence is the same for both media

If the elemental compositions of w and m is not similar, the backscattering of photons at the boundary can change significantly the photon fluence, regardless of the dimensions of w

3.4. CAVITY THEORY

3.4.3. Other cavity sizes

When the energy of photon has a spectrum of energies, D_m/D_w is obtained by integrating :

$$\frac{D_m}{D_w} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_m}{\left(\frac{\mu_{en}}{\rho}\right)_w} \Rightarrow \frac{D_m}{D_w} = \frac{\int_0^{h\nu_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}h\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_m h\nu \ \mathrm{d}(h\nu)}{\int_0^{h\nu_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}h\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_w h\nu \ \mathrm{d}(h\nu)} \equiv \left(\frac{\overline{\mu}_{en}}{\rho}\right)_w^m$$

$\left(\frac{\overline{\mu}_{en}}{\rho}\right)_w^m$ **is an average ratio of mass absorption energy coefficients, which takes into account:**

- **the photon spectrum that irradiates equally both materials *w*, considered a large cavity**
- ***m***

3.4. CAVITY THEORY

3.4.3. Burlin cavity theory

In Burlin's theory:

- **cavities have intermediate sizes**
- **cavity and medium are in CPE**
- **elemental compositions of both are similar**

$$\frac{D_g}{D_w} = d\,\bar{\bar{S}}_w^{\,g} + (1-d)\left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^g$$

parameter d assumes values between 0 and 1 according to the cavity dimensions:

- **$d \to 1$ for small cavities**
- **$d \to 0$ for large cavities**

3.5. PRACTICAL DOSIMETRY WITH ION CHAMBERS

Ionization chambers are frequently used in diagnostic radiology

They usually are built with a wall

- **that works like a large cavity with gas**
- **with thickness that guarantees CPE**

If the elemental composition of this wall *w* is similar to the composition of the medium *m* where the dose is to be measured, and there is CPE also in the medium, it is possible to relate the dose in the medium to the dose in the wall with expressions:

$$\frac{D_m}{D_w} = \frac{\left(\frac{\mu_{en}}{\rho}\right)_m}{\left(\frac{\mu_{en}}{\rho}\right)_w}$$

$$\frac{D_m}{D_w} = \frac{\int_0^{h\nu_{max}} \left(\frac{d\Phi}{dh\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_m h\nu \; d(h\nu)}{\int_0^{h\nu_{max}} \left(\frac{d\Phi}{dh\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_w h\nu \; d(h\nu)} \equiv \left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^m$$

3.5. PRACTICAL DOSIMETRY WITH ION CHAMBERS

When the gas inside the ion chamber is irradiated mainly by the charged particles released in the wall and which cross the gas volume, the dose to the material where the chamber is inserted is:

$$D_m = D_g \; \bar{\bar{S}}_g^{\,w} \left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^m$$

obtained comparing the equations:

$$\frac{D_w}{D_g} = \frac{\displaystyle\int_{T_{\min}}^{T_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}T}\right)_w \left(\frac{\mathrm{d}T}{\rho \mathrm{d}x}\right)_{c,w} \mathrm{d}T}{\displaystyle\int_{T_{\min}}^{T_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}T}\right)_w \left(\frac{\mathrm{d}T}{\rho \mathrm{d}x}\right)_{c,g} \mathrm{d}T} = \bar{\bar{S}}_g^{w}$$

$$\frac{D_m}{D_w} = \frac{\displaystyle\int_0^{h\nu_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}h\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_m h\nu \; \mathrm{d}(h\nu)}{\displaystyle\int_0^{h\nu_{\max}} \left(\frac{\mathrm{d}\Phi}{\mathrm{d}h\nu}\right)_m \left(\frac{\mu_{en}}{\rho}\right)_w h\nu \; \mathrm{d}(h\nu)} \equiv \left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^m$$

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3.5. PRACTICAL DOSIMETRY WITH ION CHAMBERS

If the charge (Q) produced in the gas and the mass of the gas (m_g) are known, the dose to the material where the chamber is inserted is:

$$D_m = \frac{Q}{m_g} \overline{W}_g \; \bar{\bar{S}}{}_g^{w} \left(\frac{\bar{\mu}_{en}}{\rho} \right)_w^m$$

$\overline{W}_g$ **is the mean energy spent in the gas to form an ion pair**

3.5. PRACTICAL DOSIMETRY WITH ION CHAMBERS

A particularly useful (and common) situation occurs when the wall of the chamber is made of a material with the same atomic composition as the cavity

The dose to cavity and dose to wall are considered equal

For chambers with gas equivalent wall, the dose to the material is:

$$D_m = D_g \left(\frac{\mu_{en}}{\rho} \right)_g^m \qquad D_m = \frac{Q}{m_g} \overline{W}_g \left(\frac{\overline{\mu}_{en}}{\rho} \right)_g^m$$

3.4. PRACTICAL DOSIMETRY WITH ION CHAMBERS

$$D_m = D_g \, \bar{\bar{S}}_g^{\,w} \left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^m$$

$$D_m = D_g \left(\frac{\mu_{en}}{\rho}\right)_g^m$$

$$D_m = \frac{Q}{m_g} \overline{W}_g \, \bar{\bar{S}}_g^{\,w} \left(\frac{\bar{\mu}_{en}}{\rho}\right)_w^m$$

$$D_m = \frac{Q}{m_g} \overline{W}_g \left(\frac{\bar{\mu}_{en}}{\rho}\right)_g^m$$

The use of above equations for obtaining the dose to the material, in practice is not trivial, as:

- **the spectra of photons and electrons are not known in general**
- **the charge is not completely collected**

But this is done for standard chambers employed for the calibration of the instruments used in diagnostic radiology, applying correction factors for incomplete charge collection and mismatch of atomic compositions. A standard chamber is compared to the instrument to be calibrated, irradiating both with well characterized photon beams, with qualities comparable to the clinical beams

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