Radiotherapy dosimetry

Aims:

- to understand the basic concepts of dosimetry
- to understand the application of dosimetry to radiotherapy

Syllabus:

- Revision of basic concepts; Absorbed dose, Kerma, charged particle equilibrium.
- Bragg-Gray theory, improvements and corrections.
- Dosimeters.

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Dosimetry

Definition of terms

Three quantities exist that are useful for describing the interactions of a radiation field with matter; *kerma K, absorbed dose D and exposure X.*

Useful quantities:

Fluence Φ - $\Phi = \frac{dN}{da}$ (m^{-2} or cm^{-2})

where N is number of rays/particles,
a is cross sectional area

Energy fluence Ψ - $\Psi = \frac{dR}{da}$ (Jm^{-2})

where R is total energy (summed energy of each ray/particle)

Exposure X

- by convention it is only applied to x- and γ-rays
- a measure of the amount of ionisation produced in a mass of air under standard conditions $\rightarrow$ a measure of photon flux at point of interest

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

C kg^{-1}, *or*, R (*Roentgen = 2.58 x 10*$^{-4}$ Ckg^{-1})

Requirements for exposure definition:

- photons interact in a defined mass of air
- all ions of one sign are measured
  & all charged particle energy is dissipated
- some energy lost by radiative process
  ionisation caused by bremsstrahlung ***not*** to be included

Relationship with energy fluence

Consider the following;

1. the charged particle energy released per unit mass of air is given by

$$\Psi\left(\frac{\mu_{en}}{\rho}\right)_{air}$$

where Ψ is the energy fluence.

2. if average energy required to produce an ion pair in air is W_{air} then, number of ion pairs per unit mass is

$$\Psi\left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \frac{1}{W_{air}}$$

3. and so the charge Q produced per unit mass (i.e. the exposure X) will be given by

$$X = \Psi\left(\frac{\mu_{en}}{\rho}\right)_{air} \cdot \frac{e}{W_{air}}$$

where

W is the mean energy expended in a gas per ion formed.
W may be regarded as a constant for each gas, independent of photon energy, for x- and γ-ray energies above a few keV.

The value in air is given by $W_{air}/e = 33.97$ J/C

This equation shows that

Energy fluence $\propto$ exposure for any given photon energy or spectrum
$\rightarrow$ can characterise x-ray field at a point using exposure value.

Note/ interaction coefficient is $\frac{\mu_{en}}{\rho}$. It describes the probability of energy being absorbed in the material quoted.

Kerma K

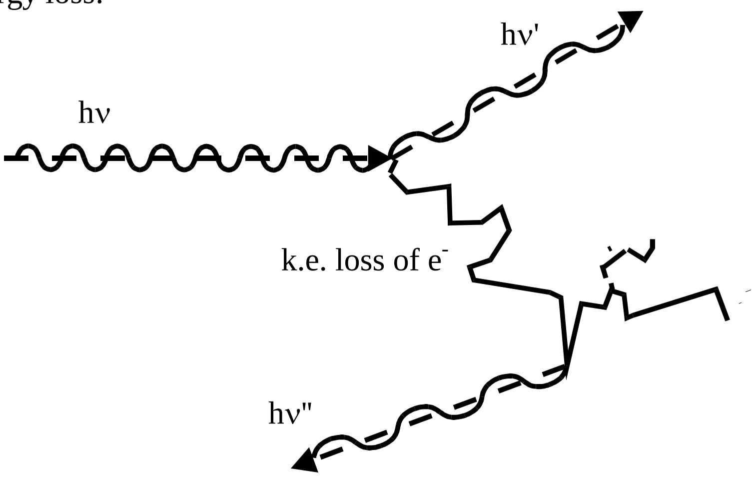
*KERMA - **K**inetic **E**nergy **R**eleased per unit **MA**ss*

quantity introduced to emphasise 2-stage process by which photons/neutrons impart energy to matter

1st stage: uncharged particles transfer energy to the k.e. of charged particles
2nd stage: these charged particles impart energy to matter

Only applies to indirectly ionising radiation (photons/neutrons)

Two stage energy loss:



$$K = \frac{dE_{tr}}{dm} \qquad (\text{J kg}^{-1} \textit{ or } \text{Gy})$$

where

dE$_{tr}$ is the sum of the initial kinetic energies of the charged particles liberated by the photons or neutrons.

dm is mass of material

dE$_{tr}$ includes the energy these charged particles later radiate as x-rays.

Note/ it is necessary to always reference material concerned because the value is material dependent.

Relationship with energy fluence

For monoenergetic photons kerma is related to the energy fluence Ψ by

$$K = \Psi\left(\frac{\mu_{tr}}{\rho}\right)$$

Components of kerma

Kerma often split into 2 parts depending on how the kinetic energy of the electrons is dissipated;

1. Coulomb interactions with electrons of absorbing material → ionisation, excitation near electron track → *collision* interactions
2. Interactions with Coulomb field of nuclei → bremsstrahlung x-rays, energy carried far from electron track → *radiative* interactions

so, $K = K_c + K_r$

Collision kerma

$$K_c = \frac{dE_{tr}^n}{dm}$$

where

E_{tr}^n is the net energy transferred

it is equivalent to energy transferred minus the radiative energy.

So, as before $$K_c = \Psi\left(\frac{\mu_{en}}{\rho}\right)$$

Note/ for collision Kerma use mass energy absorption coefficient, whereas for total Kerma use mass energy transfer coefficient

Absorbed dose, D

Applies to both directly and indirectly ionising radiation.

Absorbed dose is a measure of the energy actually deposited within a known mass of material

$$D = \frac{d\bar{e}}{dm} \qquad \text{(J kg}^{-1} \textit{ or } \text{Gy)}$$

Where $d\bar{e}$ is the mean energy imparted by ionising radiation to material of mass dm

mean energy imparted $e = \sum R_{in} - \sum R_{out}$

where

ΣR_{in} is the radiant energy incident on the volume, i.e. the sum of the energies (exc. rest mass energies) of all those charged & uncharged particles which enter the volume,

ΣR_{out} is the radiant energy emerging from the volume, i.e. the sum of the energies (exc. rest energies) of all those charged & uncharged particles which leave the volume,

All radiation effects in matter depend in some manner on D

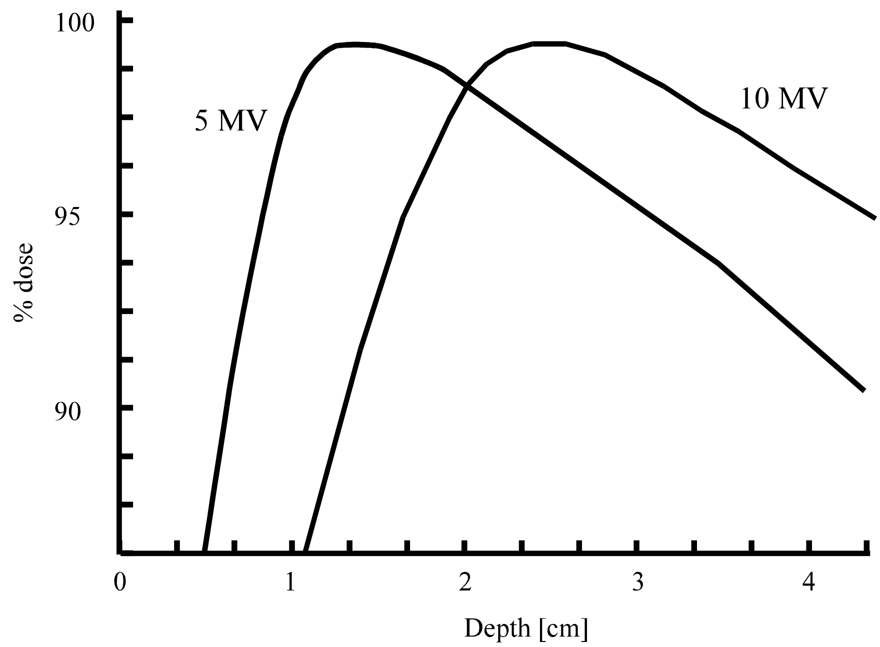
→ most important quantity.

Depth dose

In radiotherapy maximum amount of dose needs to be deposited at the region of interest.

Dose varies with depth into the tissue.

Case is for a 5 and a 10 MV photon beam incident on water



- absorbed dose at surface layer is small as few electrons are released
  - most of the energy is actually from electrons scattered back
  - go deeper and the fluence of electrons increases from the contribution of overlying layers
  - so, absorbed dose also increases
  - eventually the increase in electron fluence is balanced by the photon attenuation
  - photon attenuation means a decrease in electrons at deeper layers
  - continuous decrease in electrons & absorbed dose with depth

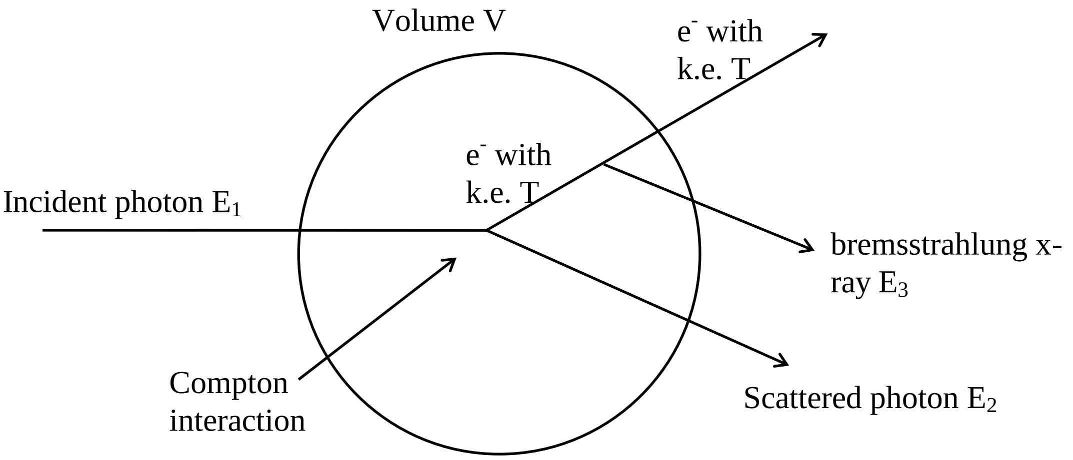
Clinical applications

The depth of the treatment volume within the body dictates the energy of the beam to be used. The deeper the volume the greater the energy.

Skin tumours typically require 50 – 100 kV x-rays,
whereas deep tumours require 2 – 10 MV x-rays typically.

Comparison between K, K_c and D

Consider following interactions in and around a volume V;



By definition:

Kerma $K = (E_1 - E_2) / m$

Collision Kerma $K_c = (E_1 - E_2 - E_3) / m$

Absorbed dose $D = (E_1 - E_2 - E_3 - T) / m$

Relationships between K, X and D

Relationship between K_c and X

We know that $$X = \Psi \left(\frac{\mu_{en}}{\rho}\right)_{air} \frac{e}{W_{air}}$$

and $$K_{c_{air}} = \Psi \left(\frac{\mu_{en}}{\rho}\right)_{air}$$

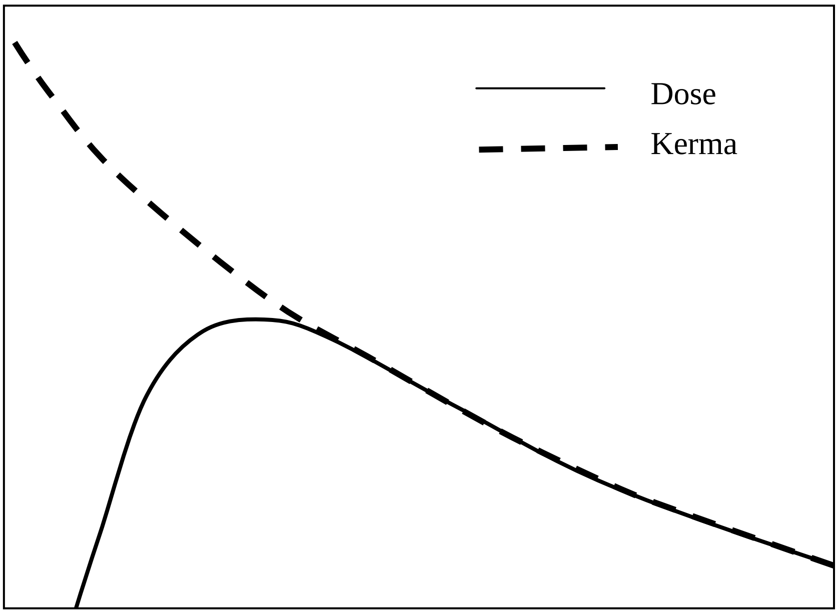
therefore, substituting for Ψ

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

Relationship between K and D

The relationship between K & D is more subtle

- Energy transfer in Kerma occurs at a point where the photon gives kinetic energy to the electron
- Dose occurs where the electron later collides with other atoms, and so is distributed.



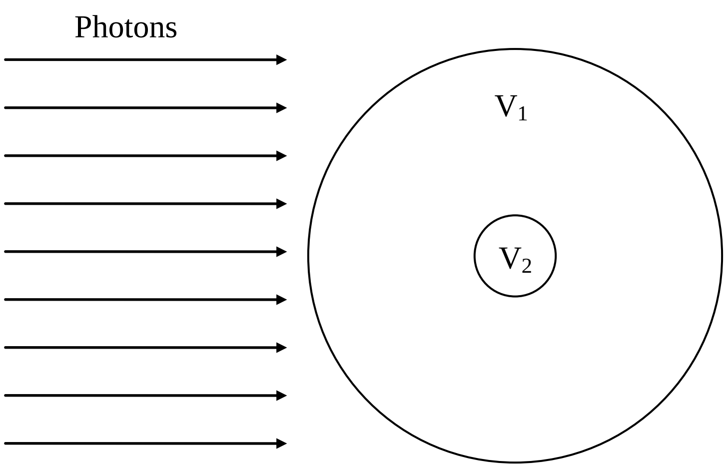
Depth

- kerma is highest at entry point and then decreases due to photon attenuation

In order to relate absorbed dose to kerma and exposure mathematically we need to introduce the concept of charged particle equilibrium CPE.

Charged Particle Equilibrium (CPE)

Consider a large volume V_1 uniformly irradiated by photons (negligible attenuation in air)



- a number of e^-s released in V_2 will travel partly through V_2 and partly through V_1 producing ions
- V_1 is sufficiently large that e^-s from V_2 are completely stopped

→ every volume such as V_2 in V_1 will undergo the same interactions

i.e. the photons & number of e^-s released & their energy and direction distribution are the same

→ from symmetry there is no build-up of secondary e^-s in V_2

→ there will be on average the same number, energy & direction of the e^-s entering V_2 as leaving it

→ Charged particle equilibrium

Following conditions required;
composition and density of the medium is homogeneous
uniform field of indirectly ionising radiation
negligible attenuation in medium
no inhomogeneous electric or magnetic fields

Causes of CPE to fail
If any of the above conditions are not met then CPE might not occur.
Possible practical causes are;
Proximity to a source: field will be non-uniform
Beam not sufficiently large to irradiate whole volume
Boundary between media within larger volume

Determination of D via X or K_{air}

Under charged particle equilibrium,

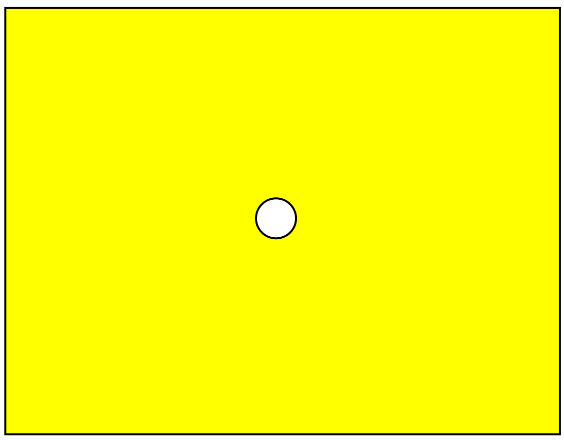
$$D = K_c$$

because number of charged particles entering will be cancelled out by number leaving.

and it follows that $$D_{air} = X\left(\frac{W_{air}}{e}\right)$$

Measurement of patient dose

- Say we want to know the dose at point A in a medium
- To measure D we must introduce a radiation sensitive device into it.
- But, the device usually not the same material
  - usually a gas-filled cavity



How do we relate the dose in the cavity to the dose in the material surrounding the cavity?

Bragg Gray cavity theory

To measure D in a medium we must introduce a radiation sensitive device into it.
But, the device usually not the same material - usually a gas-filled cavity

How do we relate the absorbed dose in the device to the dose in the medium?

Theory proposed which has following assumptions;

- cavity is so small that it does not disturb the CP fluence or it's energy & direction
- absorbed dose in cavity is assumed to be deposited entirely by charged particles crossing it (secondary charged particles lose energy by continuous slowing down, i.e. large no. of small E loss events)

If this is the case then the following equation applies

$$D_m = D_{air} \frac{\left(\frac{\mu_{en}}{\rho}\right)_m}{\left(\frac{\mu_{en}}{\rho}\right)_{air}} \quad \text{where} \quad D_{air} = X\left(\frac{W_{air}}{e}\right) \quad \text{(as we've seen before)}$$

So, absorbed dose in medium immediately surrounding cavity can be calculated providing the other values in equation are known.

The Fano theorem

Fano attempted to prove theoretically the Bragg-Gray assumption that the presence of a cavity did not affect the electron fluence was most likely if the gas in the chamber had a similar elemental composition to the medium.

Fano's theorem

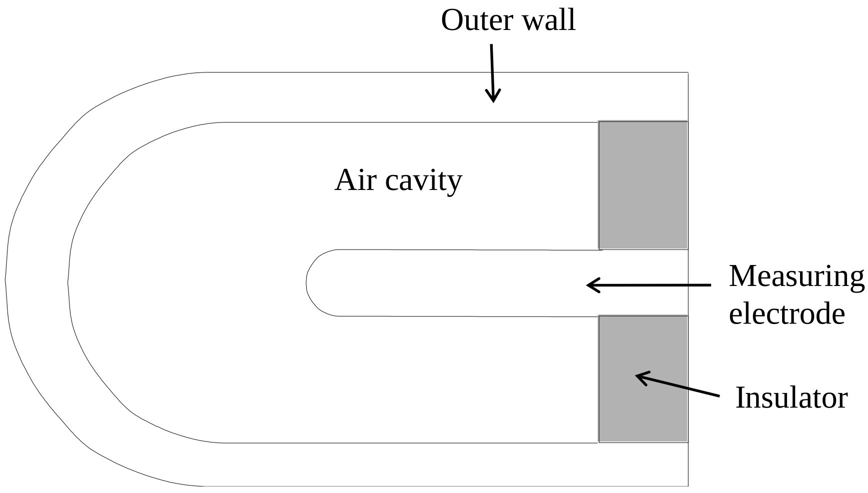
electron fluence in a medium is independent of density variations

Implications:

- Cavity does not need to be so small.
- introduction of a low-density cavity into a material would not alter the electron fluence providing the material in the cavity has the same elemental composition

Ionisation chamber

Uses charged particle equilibrium – air cavity is inner volume, outer wall is outer volume.
Needs CPE so that electrons leaving air cavity will be replaced – keeps charge constant
Fano theorem says that any air equivalent material (e.g. certain plastics) can make the wall.



- charge generated in cavity is measured to give Q
- mass of air in cavity calculated from known volume
- Therefore exposure can be measured.

Ionic recombination

Some positive and negative ions recombine in the gas, which means that the charge measured is less than the ionisation caused.