Módulo :: Dosimetría – 4/5/2018 14:00-17:00

Basic concepts of dosimetry and particularities in BNCT

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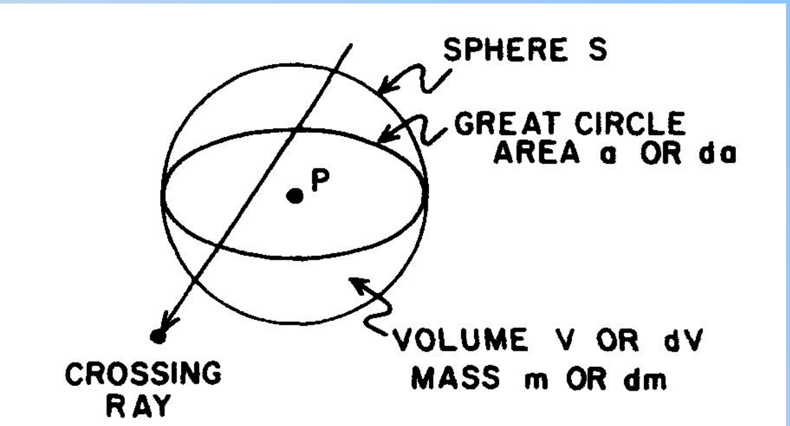
- Radiation field quantities (fluence, flux, etc...) describe the radiation field alone, they generally refer to an “in vacuum” situation
- Dosimetry quantities: radiation-matter interactions are “turned on” so it is possible to study the amount (and the way) of energy which actually goes from radiation into matter



Kerma (Kinetic Energy Released in MAtter)

- Only for indirect ionizing radiation and always specify the matter of interest
- Kerma is used to describe the first step of energy transfer by indirect ionizing radiations (two step process) to matter, that is the energy transferred to secondary (directly ionizing, charged) particles which actually will deposit energy into matter

Kerma (Kinetic Energy Released in MAtter)

- Kerma is defined starting from the stochastic quantity *energy transferred* ε_{tr} and the *radiant energy R* (i.e., the energy of particles, excluding the rest mass, emitted, transferred r received)

$$\varepsilon_{tr} = (R_{in})_N - (R_{out})_N^{non\_rad} + \Sigma Q$$

where

$(R_{in})_N$ = radiant energy of non charged particles entering the volume of interest V;

$(R_{out})_N^{non\_rad}$ = radiant energy of non charged particles leaving volume V, excluding the energy released by radiative losses* suffered by the charged particles set in motion inside the volume V (* conversion of charged particle kinetic energy to photon energy , i.e. bremsstrahlung x-rays production or in-flight annihilation of positrons)

ΣQ = energy deriving from rest mass inside volume V

Any kinetic energy passed from one charged particle to another is not counted in ε_{tr}

Kerma (Kinetic Energy Released in MAtter)

- ε_{tr} is the kinetic energy trasferred from the incident non charged radiation to the secondary charged particles inside volume V.

$$\mathbf{K = d\langle\varepsilon_{tr}\rangle / dm}$$

where $d\langle\varepsilon_{tr}\rangle$ is the expectation (mean) value of energy transferred inside V due to the stochastic nature of ε_{tr}

K is then the expectation value of kinetic energy transferred to charged particles per unit of mass around the point of interest, INCLUDING the energy which is released by radiative loss of charged particles set in motion in V but excluding energy exchange between two charged particles

- Unit: Gray (Gy)

$$1\ \text{Gy} = 1\text{J}\cdot\text{kg}^{-1} \qquad 1\ \text{Gy} = 100\ \text{rad}$$

Photons: relation between K and energy fluence (Ψ).

- Mass energy transfer coefficient $(\mu_{tr}/\rho)_{E,Z}$ (E = energy of photon; Z = atomic number of matter)
- It represents the fraction of the incident energy EN (N = number of monoenergetic incident photons) trasferred to the charged particles as kinetic energy.
- Knowing the energy fluence of the field:

$$K = \Psi \cdot (\mu_{tr}/\rho)_{E,Z}$$

(in case of non monochromatic field:

$$K = \int_{[Emin\text{-}Emax]} \Psi(E) \cdot (\mu_{tr}/\rho)_{E,Z} \cdot dE)$$

Neutrons: relation between K and (particle) fluence Φ.

- The basic relation is the same but for neutrons we define the KERMA FACTORS

$$(F_n)_{E,Z} = E \cdot (\mu_{tr}/\rho)_{E,Z}$$

and refer to (neutron) fluence Φ

- Monoenergetic neutrons:

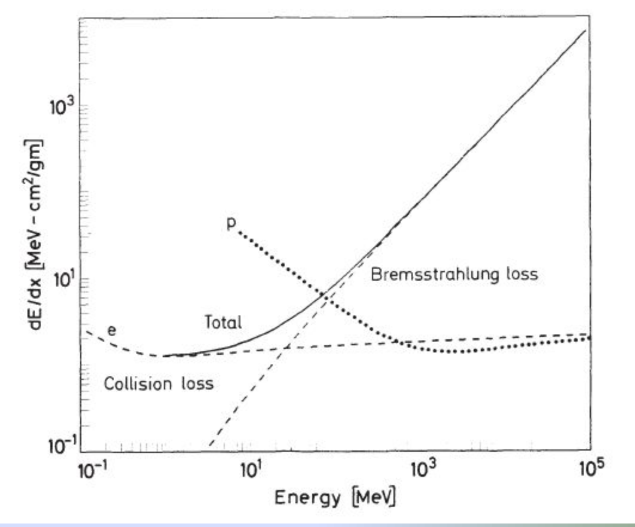
$$K = \Psi \cdot (\mu_{tr}/\rho)_{E,Z} = \Phi \cdot E \cdot (\mu_{tr}/\rho)_{E,Z} = \Phi \cdot (F_n)_{E,Z}$$

(in case of non monochromatic field:

$$K = \int_{[Emin-Emax]} \Phi\,(E) \cdot (F_n)_{E,Z} \cdot dE)$$

- if K in Gy (or rad), then $[(F_n)_{E,Z}] = Gy \cdot cm^2/neutron$

Components of Kerma



- Once electrons (positrons) are set in motion, they can loose their energy by collisions or by radiation emissions
- It is then useful to defined two components of K

$$\mathbf{K = K_{coll} + K_{rad}}$$

where

K_{coll} = kinetic energy transferred by charged particles through direct collisions (i.e., a **local** energy release close to the charged particle track)

K_{rad} = kinetic energy lost by emission of photons (they transport energy **far** from the track of the charged particle)

- If the primary radiation is photons of low energy: K_{rad} not significant; if primary radiation is made by neutrons, secondary charged particles are heavy ions (p, α, etc...), radiative loss no significant so $K \cong K_{coll}$

Components of Kerma

- K_{coll} can be defined by a stochastic quantity, the *net energy transferred* ε_{tr}^{net}

$$\varepsilon_{tr}^{net} = (R_{in})_N - (R_{out})_N^{TOT} + \Sigma Q$$

$$\varepsilon_{tr}^{net} = (R_{in})_N - (R_{out})_N^{non\_rad} \mathbf{- (R_{out})_N^{rad}} + \Sigma Q = \varepsilon_{tr} - (R_{out})_N^{rad}$$

that is, the energy transferred to charged particles as kinetic energy (ε_{tr}) minus the energy loss by radiative interactions

- Indicating by *g* the fraction of kinetic energy of charged particles lost by radiative emissions then we have

$$\varepsilon_{tr}^{net} = \varepsilon_{tr}\,(1-g)$$

so K_{coll} can be expressed as:

$$\mathbf{K_{coll} = d\langle \varepsilon_{tr}^{net} \rangle / dm}$$

Components of Kerma

$$\mathbf{K_{coll} = d< \boldsymbol{\varepsilon}_{tr}^{net} > / \ dm}$$

- thus K_{coll} is the expectaion value of the net energy transferred to charged particles per unit mass at a point of interest, excluding both the radiative loss energy and the energy passed from ne charged particles to another

Dose D

- Most important dosimetric quantity, but very difficul to measure
- To describe energy imparted by all kind of ionizing radiation (but delivered by charged particles)
- Defined from the stochastic quantity *energy imparted* ε

$$\varepsilon = (R_{in})_N - (R_{out})_N + (R_{in})_C - (R_{out})_C + \Sigma Q$$

where

$(R_{in})_N$, $(R_{out})_N$ are the radiant energy associated with the incident and escaping non charged particles from volume V, respectively

$(R_{in})_C$, $(R_{out})_C$ are the radiant energy associated to charged particles incident and escaping from volume V, respectively

ΣQ the net amount of mass-energy transformations in V

Dose D

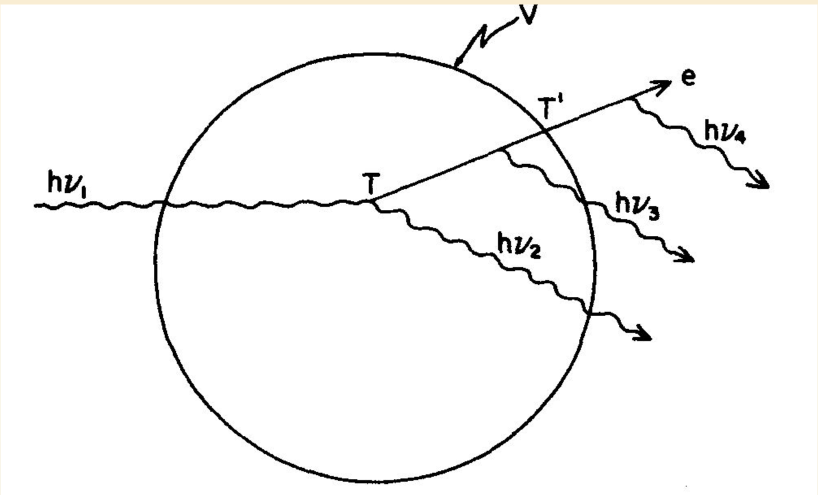
$$\mathbf{D = d\langle \varepsilon \rangle / dm}$$

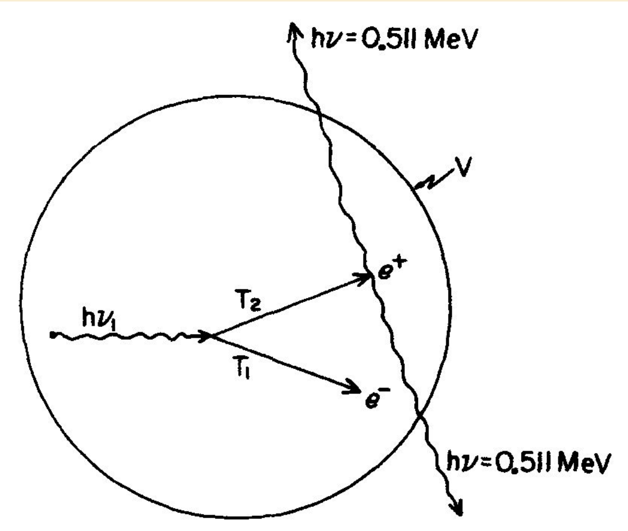
where

d<ε> = expectation (mean) value of energy imparted in volume V around the point of interest.

- D represents the energy per unit mass which remains in the mater at P to produce any effects attributable to the radiation.
- Unit: $1 J \cdot kg^{-1} = 1 Gy$
- It is generally difficult to find an easy and straight relationship between D and any radiation field quantity (easier to measure). This is mainly due to the fact that there is always a fraction of energy imparted released outside the volume V; in addition, part of the energy actually released inside V comes from outside...

Examples





Compton effect

$\varepsilon = h\nu_1 - (h\nu_2 + h\nu_3 + T') + 0$

$\varepsilon_{tr} = h\nu_1 - h\nu_2 + 0 = T$

$\varepsilon_{tr}^{net} = h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4) + 0 = T - (h\nu_3 + h\nu_4)$

Pair production

$\varepsilon = 0 - (1.022 + T_3) + h\nu_1 = T_1 + T_2 + T_3$

$\varepsilon_{tr} = 0 - 1.022 + h\nu_1 = T_1 + T_2$

$\varepsilon_{tr}^{net} = 0 - 1.022 - T_3 + h\nu_1 = T_1 + T_2 - T_3$

Exposure X

- Only for electromagnetic waves and air

$$\mathbf{X = dQ / dm}$$

where

dQ = the absolute value of the total of the ions of one sign produced in air when all the electrons (negative and positive) liberated by photons in the volume of air of mass dm are completely stopped in air

dm = mass of the volume around the point of interest

- What does it mean?!

X is the ionization equivalent of the collision kerma K_{coll} in air for X and gamma rays

- By definition, X does not include the ionizations coming from photons produced by radiative losses of charged particles
- Unit: [X] = C/kg; more common Roetgen R (production of 1esu of each sign in an air mass of $1cm^3$ at 1atm and 0°C)

$$1R = 2.58 \cdot 10^{-4}\ C/kg$$

Exposure X

- As in the case of K, we can derive direct relationships between X and radiation field quantities (energy fluence of the photon field)
- *Mean energy expected in a gas per ion pair producion*: W
- We want to calculate a *ionization equivalent of the collision kerma* K_{coll} so in defining W we must neglect the kinetic energy involved in radiative emissions

Exposure X

- We define:

T_i = initial kinetic energy of electron i (set in motion by a primary photon in V...)

g_i = fraction of T_i involved in radiative emissions along the whole air-path of the electron

then $(1-g_i)$ = fraction of T_i involved in collissions

then for many electrons: $T_{tot} = \Sigma\, T_i\,(1-g_i)$

Regarding the field, N_i = total number of ion pairs produced in air by electron i, while g_i' = fraction of ion pairs due o radiative losses

$(1-g_i')$ = number of ion pairs due to collisions along electron track

then $N_{tot} = \Sigma\, N_i\,(1-g_i')$ = total number of ion pairs due to collisions of electrons (positrons) created in V

Exposure X

- We finally have:

$$W = \Sigma\, T_i\,(1\text{-}g_i) \,/\, \Sigma\, N_i\,(1\text{-}g_i')$$

- Unit: eV/ion_pair
- In dry air W = 33.97 eV/ion_pair

- Nwe can relate X to the energy fluence (Ψ) of the primary photon field

  - monochromatic photons:

$$X = \Psi \cdot (\mu_{tr}\,/\rho)_{E,air} \cdot (1\text{-}g) \cdot (W/e)_{air}^{-1}$$

$$= \Psi \cdot (\mu_{en}\,/\rho)_{E,air} \cdot (W/e)_{air}^{-1} = (K_c)_{air} \cdot (W/e)_{air}^{-1} = (K_c)_{air}/33.97$$

  - non monochromatic photon: integration over the whole energy spectrum

Usefulness of exposure X

- Given a photon field, for each photon energy X is proportional to energy fluence; moreover, the element mix in air produces an effective atomic number Z_{eff} quite close to the one of soft tissues; in this way we can assume air as an equivalent tissue material, at least for what concern the absorption of X and gamma rays (experimental dosimetry by TE-PC...)
- Giving that

$$K_{coll} = \Psi(\mu_{en}/\rho)_{E,Z} \quad \text{and} \quad X = \Psi(\mu_{en}/\rho)_{E,Z} \cdot (W/e)_{air}^{-1}$$

then

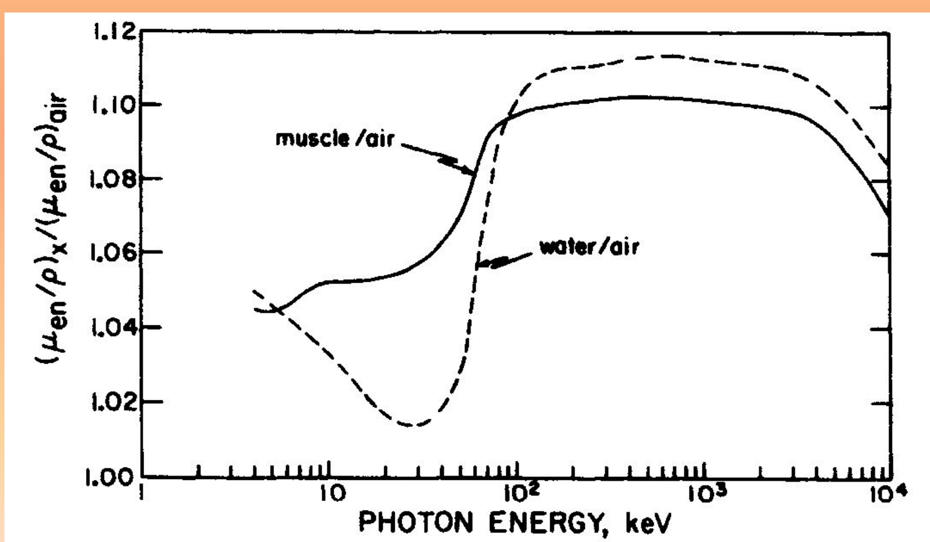
$$K_{coll}/X \propto (\mu_{en}/\rho)_{E,Z} / (\mu_{en}/\rho)_{E,air}$$

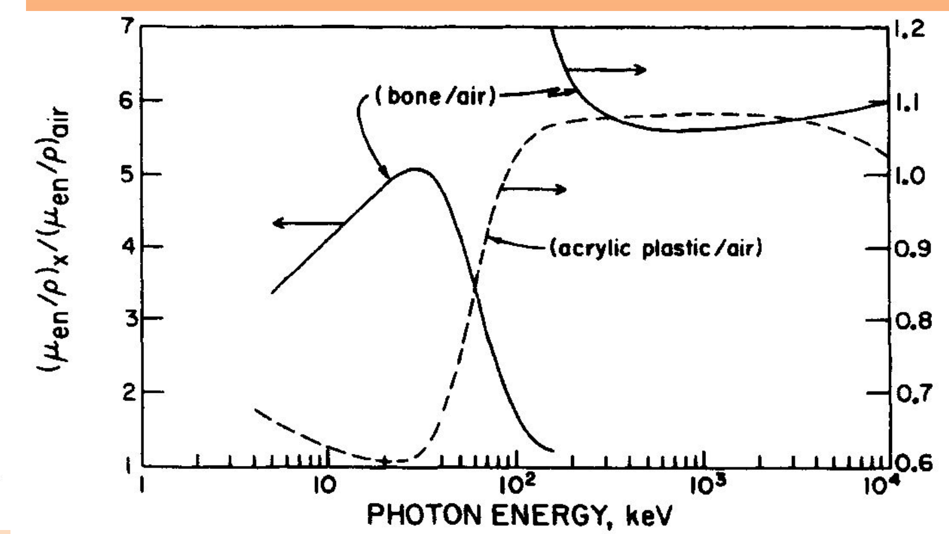
Usefulness of exposure X

$K_{coll} = \Psi(\mu_{en}/\rho)_{E,Z}$ and $X = \Psi(\mu_{en}/\rho)_{E,Z} \cdot (W/e)_{air}^{-1}$

then

$$K_{coll}/X \propto (\mu_{en}/\rho)_{E,Z} / (\mu_{en}/\rho)_{E,air}$$

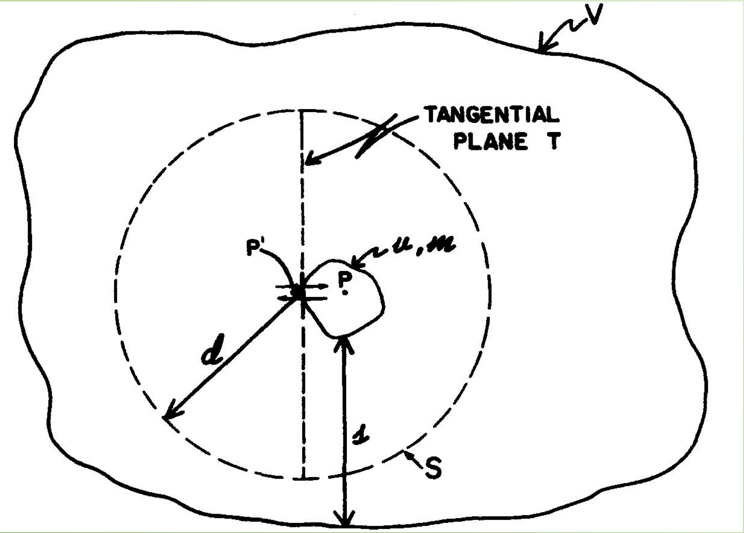




Conditions when D is easy to calculate...

- D = main dosimetric unit; fundamentl quantity to estimate the biological effects of radiation on matter
- But it is extremely difficult to measure/calculate directly, due to its direct relationship to the secondary radiation and the point in which energy is actually absorbed
- We can define particular conditions in which D is equal to K; the latter is less complicated to calculate!
- Radiation equilibrium and charged-particle equilibrium

Radiation equilibrium

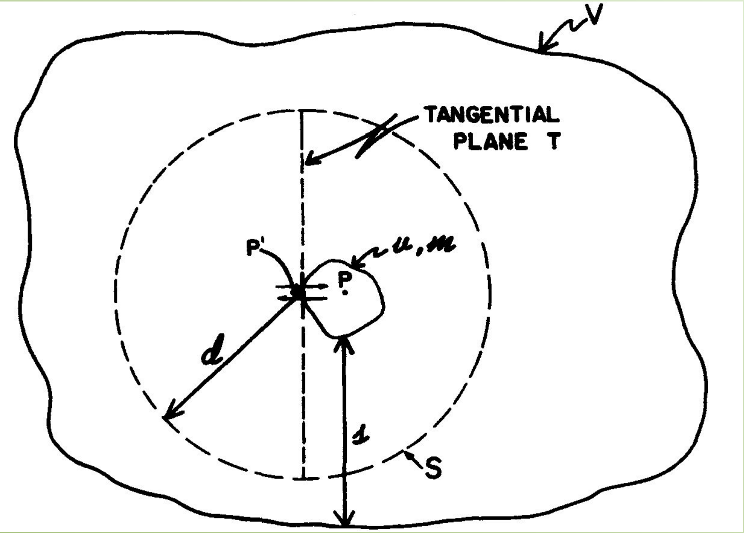


- Let's say:

  V = extended volume conteining a homogeneous medium and a homogeneous isotropic source distribution;

  v = small volume centered on the point of interest P
- The extention of V must be big enough to garantee that the maximum penetration lenght (d) of any emitted radiation and its secondaries is less than the minimum separation (s) of v from the boundary of V.
- In case of indirect ionizing radiations (photon or neutrons), we must consider their exponential attenuation; thus a maximum track lenght (range) cannot be defined. As consequence, the requirement on V is that it must be big enough to reduce to a desired value the number of radiations penetrating v.

Radiation equilibrium

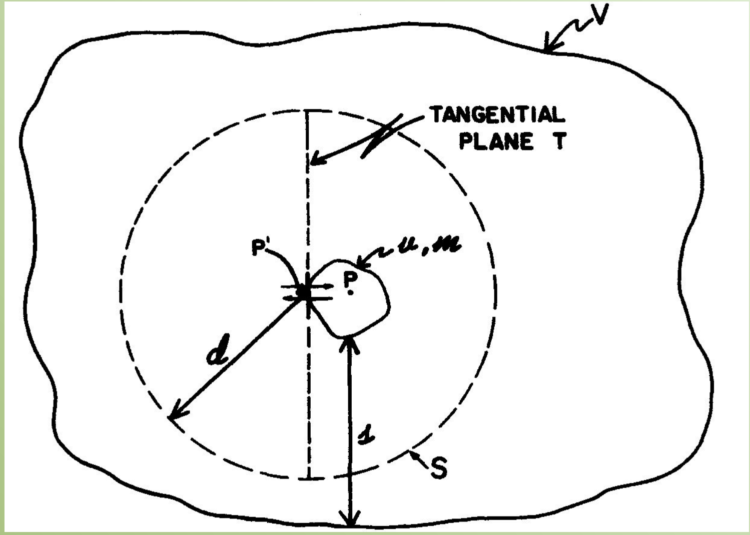


- Radiation Equilibrium (RE) is settled inside v
  if the following condition is satisfied:
  the entering radiant energy of charged and uncharged particles is balanced by the escaping ones

$$\langle R_{in} \rangle_N = \langle R_{out} \rangle_N \text{ and } \langle R_{in} \rangle_C = \langle R_{out} \rangle_C$$

- This is true when all the following conditions are satisfied:
  (1) the atomic composition of the medium is homogeneous;
  (2) the medium density is homogeneous;
  (3) no presence of electric or magnetic fields able to perturbe the track of charged particles (the felds due to the random orientation of atoms are not considered)
  (4) in presence of radioactive materials, the radioactive sources must be homogeneously distributed in V

Radiation equilibrium



- Due to the definition of energy imparted ε

$$\varepsilon \quad = (R_{in})_N - (R_{out})_N + (R_{in})_C - (R_{out})_C + \Sigma Q$$

in RE condition:

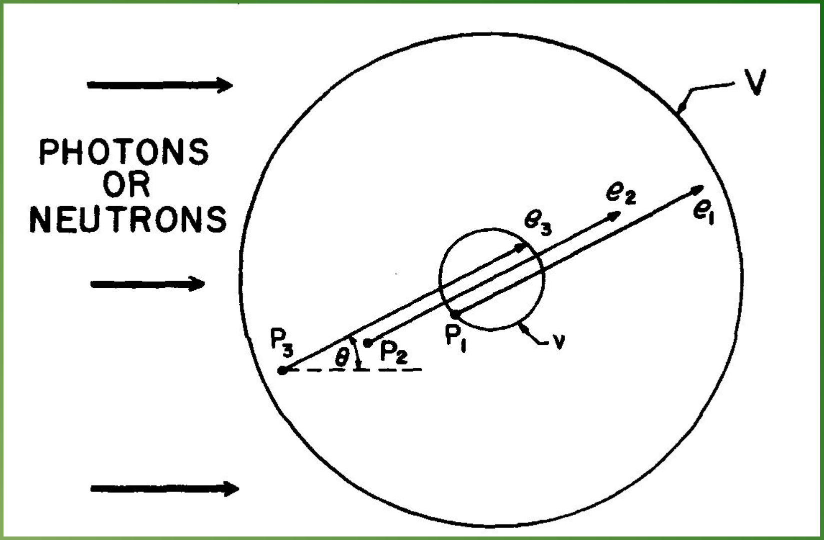
$$\varepsilon \quad = \Sigma Q$$

- In such conditin dose D is simply:

$$D = d\langle\varepsilon\rangle / dm = \Sigma Q / dm$$

- If RE exixts at a pint of a medium the absorbed dose is equal to the expectation value of the energy released by the radioactive material per unit of mass at the point.
- The concept of RE has practical importance especially in the fields of nuclear medicine and radiobiology.

Charged particle equilibrium



- CPE exists inside volume v
  if the entering radiant energy
  due to charged particles equals
  the radiant energy coming out from v due to charged particles

$$\langle R_{in}\rangle_C = \langle R_{out}\rangle C_C$$

- The previous condition is verified if the following conditions are satisfied:
  (1) the medium atomic composition is homogeneous
  (2) the medium density is homogeneous
  (3) no inhomogeneous electric or magnetc fields are present
  (4) there is a uniform field of indirect ionizing radiation with a non significan attenuation of the primary radiation along V penetration

Charged particle equilibrium

- When CPE "is on" than

$$D = K_{coll}$$

because:

$$\varepsilon \;\; = (R_{in})_N - (R_{out})_N + (R_{in})_C - (R_{out})_C + \Sigma Q$$

then in CPE

$$\varepsilon \;\; = (R_{in})_N - (R_{out})_N + \Sigma Q$$

$$\varepsilon \;\; + (R_{out})_N = (R_{in})_N + \Sigma Q$$

- If we now recall the definition of net energy transfer ε_{tr} (introduced for K_{coll}):

$$\varepsilon_{tr}^{net} = (R_{in})_N - (R_{out})_N^{non\_rad} - (R_{out})_N^{rad} + \Sigma Q$$

then we can conclude:

$$\varepsilon_{tr}^{net} = \varepsilon + (R_{out})_N - (R_{out})_N^{non\_rad} - (R_{out})_N^{rad}$$

that is

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

Charged Particle Equilibrium

- Two medium A and B, CPE conditions under photon irradiation

$$D_A / D_B = (\mu_{en} /\rho)_A / (\mu_{en} /\rho)_B$$

- Two medium A and B, CPE conditions under neutron irradiation

$$D_A / D_B = (F_n)_A / (F_n)_B$$

- In air, recalling the exposure

$$D_{air} = (K_{coll})_{air} = X \cdot (W/e)$$

When EPC is not verified?

- Inhomogenity of medium (interface between two mediums)
- Incident radiation is not uniform (vicinity of radiation source)
- Non uniform electric and magnetic fields

When EPC is not verified?

- General solution: “build up cup” method (experimental dosimetry: I add tissue equivalent around the sensitive volume to achieve linear dimensions higher than the range of charged secondaries; ATTENTION: balance with the attenuation on the primary radiation field! Problem when high energy primary radiation)

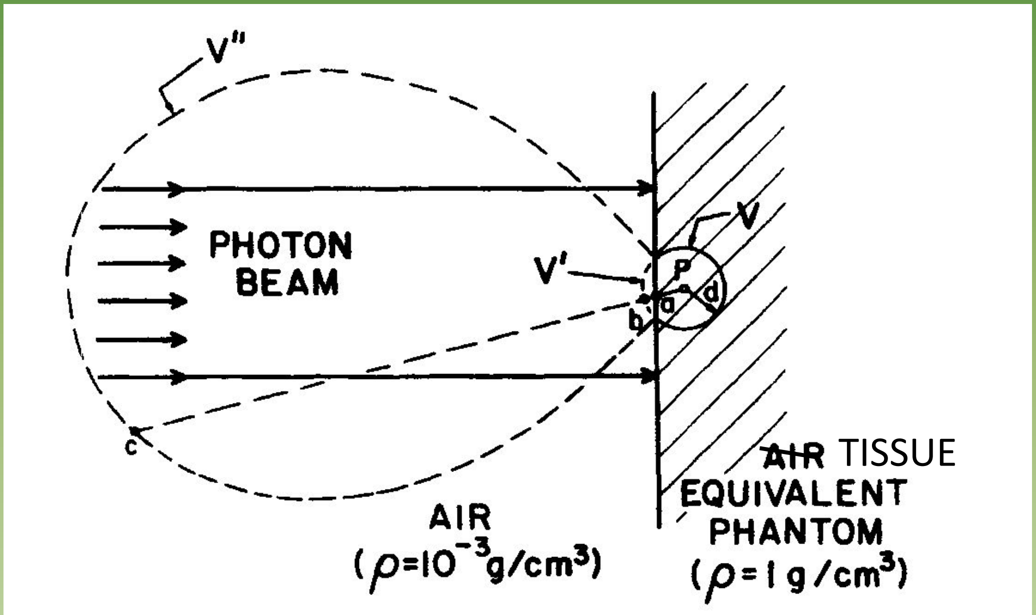
TABLE 4.1. Approximate Attenuation[a] of Gamma Rays and Neutrons within a Layer of Water Equal to the Maximum Range of Secondary Charged Particles

Primary Radiation Energy (MeV)	Gamma-Ray Attenuation (%) in Maximum Electron Range	Neutron Attenuation (%) in Maximum Proton Range
0.1	0	0
1.0	1	0
10	7	1
30	15	4

[a] For ‘‘broad-beam’’ geometry, see Chapter 3, employing μ_{en} as an effective attenuation coefficient.

When EPC is not verified?

- Interesting situation for external beam radiotherapy:

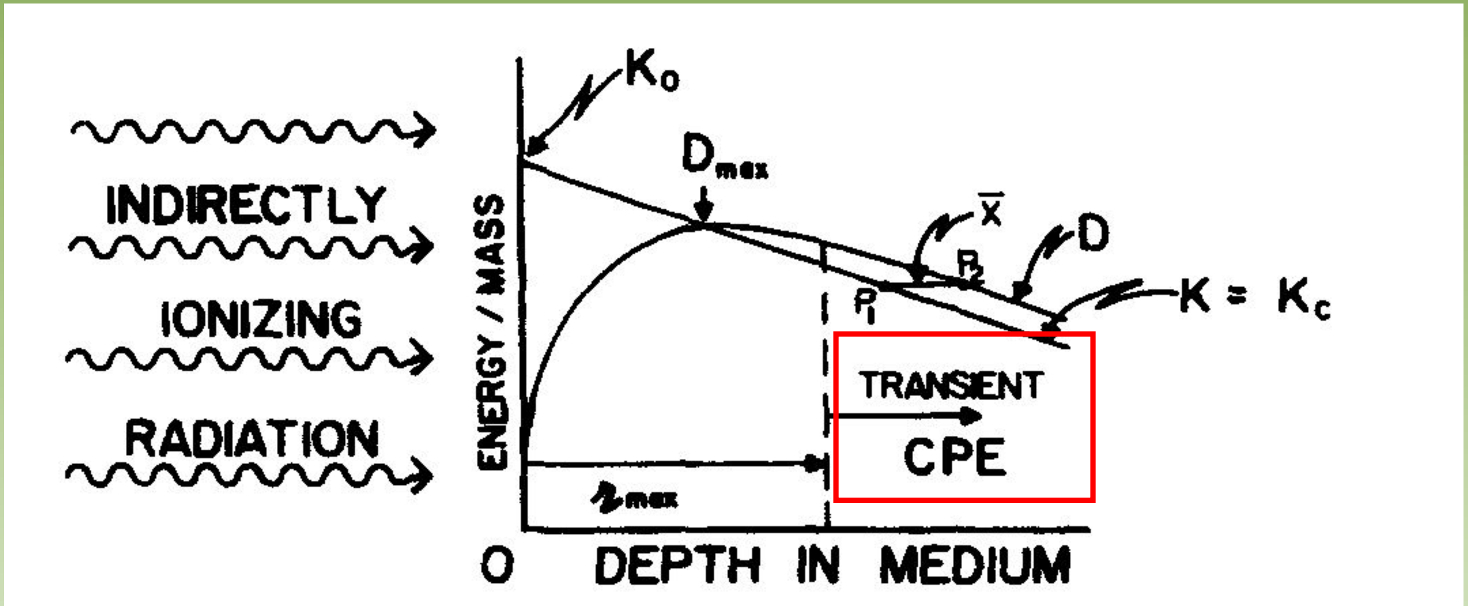


significant medium inhomogeneity (from air to tissue, density variation of almost 1000).

When EPC is not verified?

- For primary radiation energy which does not have a significant radiative loss of secondaries

$$K_{rad} = 0 \quad \text{and} \quad K = K_{coll}$$



Neutron dosimetry (few useful considerations for BNCT dosimetry)

- Natural tissue composition (ICRU 13, 1969):

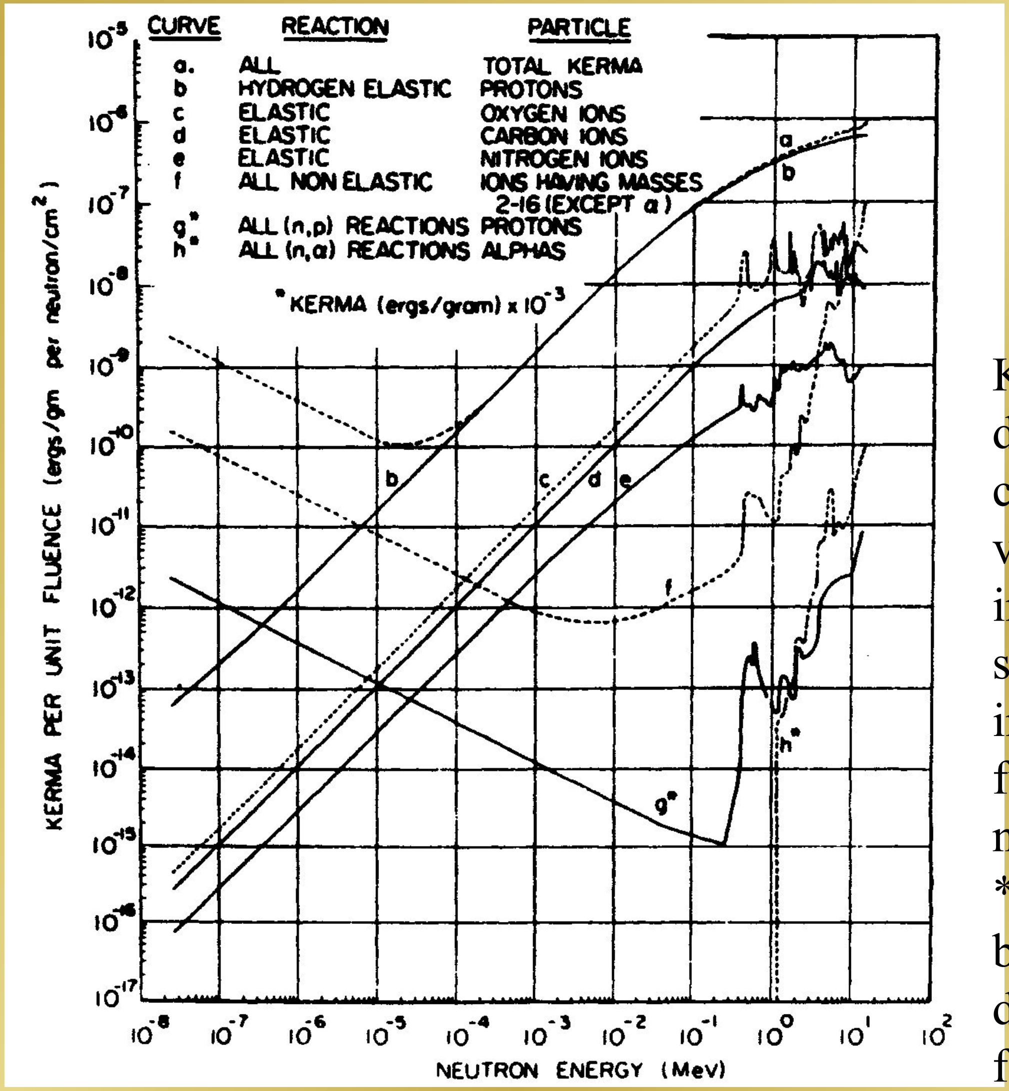
Tissue approximation	$C_5H_{40}NO_{18}$
Reference man	H(10%) C(18%) N(3%) O(65%) others (4%)
Soft tissue	H(10%) C(12%) N(4%) O(63%) ohers (1%)

- In BNCT we add a "significant" amount of ^{10}B (ppm, 10^{-6}g/g) so:

$$D\,(Gy\_w) = D_{tissue} + D_{B10} = D_N + D_{Hscat} + D_{Hgamma} + D_{B10} = RBE(p)(D_N + D_{Hscat}) + 1 \cdot D_{Hgamma} + ppm \cdot CBE \cdot D_{B10}$$

- Due to the physics of neutron production reactions, always mixed (n+γ) field

Neutron dosimetry (few useful considerations for BNCT dosimetry)



Kerma per unit flux, due to the contribution of various neutron interactions in a small mass of tissue in free space, as a function of incidente neutron energy.
*Curve g and h: must be displaced downward by a factor 10^{-3}

Bibliography

- F.H.Attix, Introduction to Radiological Physics and Radiation Dosimetry, 2004 WILEY-VCH Verlag GmbH & Co. KGaA, Wenheim
- The dosimetry of ionizing radiation, 3 volumes, Eds. Kase,Bjärngard,Attix, 1985 Academic Press Inc.
- G.F.Knoll, Radiation detection and measurements
- W.R.Leo, Techniques for nuclear and particle physics experiments. A how-to approach