

AAPM

Continuing Education
Therapy Physics Review Course

Measurement of Radiation

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Definition

Ionization

Ionization is a process in which one or more electrons are liberated from a parent atom or molecule or other bound state

Ionizing radiation

Ionizing radiation consists of charged particles (for example, positive or negative electrons, protons, or other heavy ions and/or uncharged particles (for example, protons or neutrons) capable of causing ionization by primary or secondary process.

Directly and Indirectly Ionizing Radiation

1. *Directly* ionizing radiation. Fast charged particles, which deliver their energy to matter directly, through many small coulomb-force interactions along the particle's track.
2. *Indirectly* Ionizing Radiation. X- or γ -ray photons (i.e., uncharged particles), which first transfer their energy to charged particles in the matter through which they pass in a relatively few large interactions. The resulting fast charged particles then in turn deliver the energy to the matter as above.

It will be seen that the deposition of energy in matter by indirectly ionizing radiation is thus a *two-step process*.

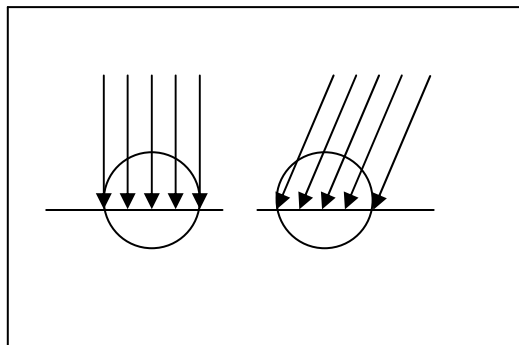
Particle Fluence

The ICRU defines particle fluence as the quotient of dN by da , where dN is the number of particles incident on a sphere of cross-sectional area da .

$$\Phi = \frac{dN}{da} \quad (1)$$

with units of M^{-2}

Care should be taken to distinguish fluence from planar fluence, which is the number of particles crossing a plane per unit area.



In the two cases shown in the figure, the particle fluence is the same because the number of particles hitting the sphere is the same in both cases whereas the planar fluence decreases when the beam is not at the normal incident.

An alternative formulation of particle fluence is that it is equal to the sum of the particle track lengths in a volume, divided by the volume. This alternative formulation is equivalent to the formal definition and we have

$$\Phi = \frac{\Sigma(\text{Tracklengths in volume})}{\text{volume}} \quad (2)$$

Consider an electron passing through a slab of area $dA \text{ cm}^2$ and thickness $t \text{ cm}$. For the moment, ignore the creation of secondary electrons. The path length in the volume is $t/\cos(\theta)$.

The electron mass collision stopping power, $(S/\rho)_{col}$, gives the energy lost to electrons in the material per unit path length (in g cm^{-2}) the energy deposited in the slab is given by:

$$E_{dep} = \frac{\rho t}{\cos(\theta)} (S/\rho)_{col} \quad (3)$$

In this simple case, the particle fluence (path length per unit volume) is given by:

$$\Phi = \frac{\frac{t}{\cos(\theta)}}{tdA} = \frac{1}{dA \cos(\theta)}$$

Substituting this into equation (3) gives

$$E_{dep} = \Phi dA \rho t (S/\rho)_{col} \quad (4)$$

From this we find

$$D = \frac{E_{dep}}{\text{mass}} = \frac{\Phi dA \rho t (S/\rho)_{col}}{\rho t dA} = \Phi (S/\rho)_{col} \quad (5)$$

This simple relationship between fluence and dose holds for arbitrary volume and fluence in any direction.

The derivation assumes that radiative photons escape from the volume of interest and secondary electrons are absorbed on the spot. This latter condition does not hold, but in conditions of charged particle equilibrium of secondary electrons, the result is still valid

because energy transported out of the volume by knock-on electrons is replaced by similar ones coming in.

Energy Fluence

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

$$\Psi = \frac{dR}{da} \quad (6)$$

Unit: JM^{-2}

Mass Energy Transfer Coefficient

The mass energy transfer coefficient, μ_{tr}/ρ of a material for uncharged ionizing particles, is the quotient of dE_{tr}/EN by PDL where E is the energy of each particle (excluding rest energy), N is the number of particles, and dE_{tr}/EN is the fraction of incident particles energy that is transferred to kinetic energy of charged particles by interactions in traversing a distance dl in the material of density ρ .

$$\frac{\mu_{tr}}{\rho} = \frac{1}{\rho EN} \frac{dE_{tr}}{dl} \quad (7)$$

Unit: M^2kg^{-1}

Mass Energy Absorption Coefficient

The mass energy absorption coefficient, of a material for uncharged ionizing particles is the product of the mass energy transfer coefficient, and $(1-g)$, where g is the fraction of the energy of secondary charged particles that is lost to bremsstrahlung in the material.

$$\frac{\mu_{en}}{\rho} = \frac{\mu_{tr}}{\rho} (1 - g) \quad (8)$$

Unit: M^2kg^{-1}

Energy Transferred, E_{tr}

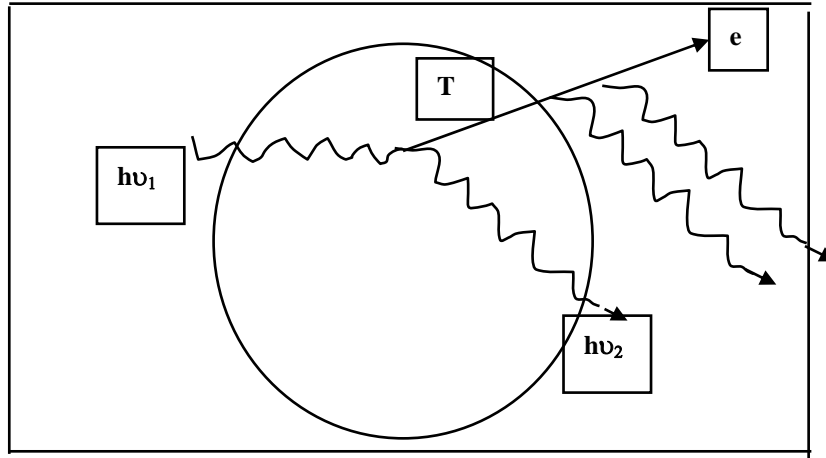
The energy transferred in a volume, V is by definition

$$E_{tr} = (R_{in})_u - (R_{out})_u^{nonr} + \Sigma Q \quad (9)$$

where $(R_{in})_u$ is the radiant energy of uncharged particles entering V , (and radiant energy is the particles energy ignoring the rest mass); $(R_{out})_u^{nonr}$ is the radiation energy of uncharged particles leaving V , except that which originated from radiative losses of kinetic energy by

charged particles while in V (i.e. except for the bremsstrahlung photons originating in V); and ΣQ is the net energy derived from rest mass in V.

E_{tr} is just the kinetic energy received by charged particles in the volume V, regardless of how they dissipate the energy.



$$E_{tr} = (R_{in})_u - (R_{out})_u^{nonr} + \Sigma Q$$

$$= h\nu_1 - h\nu_2 + 0 = T$$

Kerma

The Kerma K at a point of interest P in V is defined as

$$K = \frac{dE_{tr}}{dm} \quad (10)$$

The kerma is the expectation value of the energy transferred to charge particles per unit mass at a point of interest.

Kerma is defined for indirectly ionizing radiation only (i.e. photons and neutrons).

For monoenergetic photons, the kerma is related to the energy fluence, by:

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

where $\left(\frac{\mu_{tr}}{\rho} \right)$ is the mass energy-transfer coefficient.

Collision Kerma

Let the net energy transferred be defined for a volume V as:

$$E_{tr}^n = (R_{in})_u - (R_{out})_u^{nonr} - R_u^r + \Sigma Q \quad (11)$$

where R_u^r is the radiant energy emitted as radiative losses by the charged particles, which originated in V, regardless of where the radiative loss event occurs. Thus E_{tr}^n does not include energy going into radiative losses, where E_{tr} does.

The collision kerma, K_c is defined as

$$K_c = \frac{dE_{tr}^n}{dm} \quad (12)$$

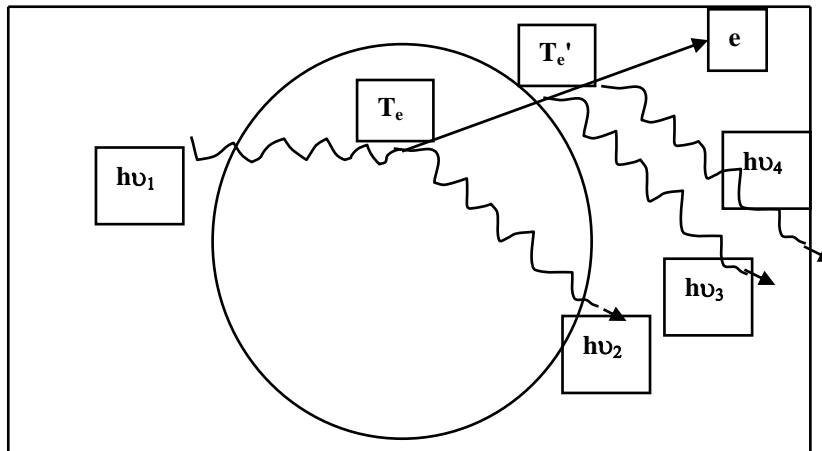
i.e. the collision kerma is the expectation value of the net energy transferred to charged particles per unit mass at the point of interest, excluding the radiative-loss energy

For monoenergetic photons,

$$K_c = \Psi \left(\frac{\mu_{en}}{\rho} \right) = E \phi \left(\frac{\mu_{en}}{\rho} \right)$$

where μ_{en}/ρ is the mass energy-absorption coefficient.

Net Energy Transferred



$$E_{tr}^n = (R_{in})_u - (R_{out})_u^{nonr} - R_u^r + \Sigma Q$$

$$=h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4) + 0$$

Absorbed Dose

The energy imparted by ionizing radiation to matter of mass m in a finite volume V is defined as

$$E = (R_{in})_u - (R_{out})_u + (R_{in})_c - (R_{out})_c + \Sigma Q \tag{13}$$

where $(R_{in})_u$ and $(R_{out})_u$ are the radiant energy of all uncharged radiation entering and leaving V , $(R_{in})_c$ and $(R_{out})_c$ are the radiant energies of the charged particles entering and leaving V .

The **Absorbed dose**, D , is the expectation value of the energy imparted to matter per unit mass at a point.

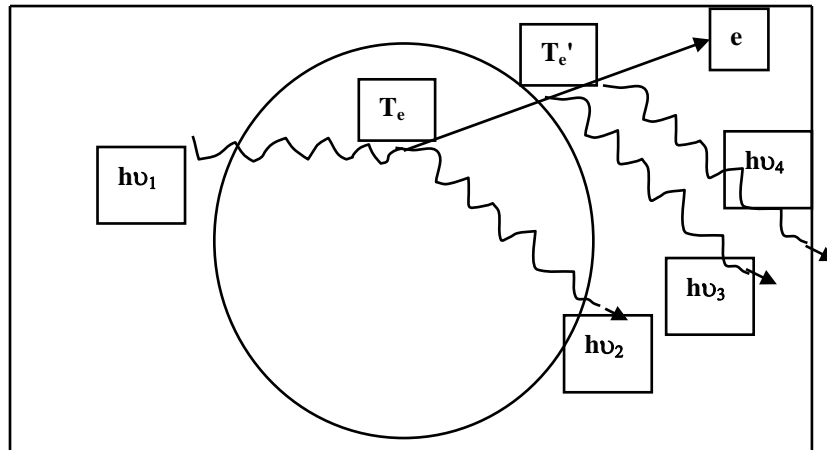
$$D = \frac{dE}{dm} \tag{14}$$

Thus, the absorbed dose D is the expectation value of the energy imparted to matter per unit mass at a point.

Energy Imparted

$$E = (R_{in})_u - (R_{out})_u + (R_{in})_c - (R_{out})_c + \Sigma Q$$

$$= h\nu_1 - h\nu_2 - (h\nu_3 + h\nu_4) + 0 - T_e' + 0$$



Exposure

Exposure is symbolized as X and defined by the ICRU as the quotient of dQ by dm where the value of dQ is the absolute value of the total charge of the ions of one sign produced in (dry) air when all the electrons liberated by photons in air of mass dm are completely stopped in air, i.e.:

$$X = \frac{dQ}{dm} \text{ (C/kg)} \quad (15)$$

Exposure is the ionization equivalent of the collision kerma in air for photons

$$\left(\frac{W}{e} \right)_{air}$$

As an electron slows down in a gas, it loses energy by ionizing the gas. The quantity W is the mean energy expended in the gas per ion pair formed, usually expressed in units of eV per ion pair. For air, this quantity is found to be a constant, independent of the electron energy above a few keV. The value is

$$\overline{W} = 33.97 \text{ eV/ ion pair}$$

A more useful form of this quantity is in terms of the charge release.

$$\left(\frac{W}{e} \right)_{air} = 33.97 \text{ (J / C)} \quad (16)$$

$(W/e)_{air}$ is the number of joules of energy deposited in the air per coulomb of charge released.

Alternatively, $(e/W)_{air}$ is the number of coulombs released per joule of energy deposited in the air.

Exposure and Air Kerma

The definition of collision kerma states that it gives the energy transferred (less radiative losses) to charge particles per unit mass. Multiplying $(e/W)_{air}$ by, the number of coulombs of charge created per joule of energy deposited will give the charge created per unit mass of air, i.e. the exposure:

$$\begin{aligned} X &= (K_c)_{air} \left(\frac{e}{W} \right)_{air} \text{ (C / kg)} \\ &= \Psi \left(\frac{\mu_{en}}{\rho} \right)_{air} \left(\frac{e}{W} \right)_{air} \end{aligned} \quad (17)$$

$$X^{cpe} = D_{air} \left(\frac{e}{W} \right)_{air}$$

The relationship between air kerma and exposure is:

$$(K_c)_{air} = \frac{\bar{w}}{e} X \quad (18)$$

or

$$(1 - g) K_{air} = \frac{\bar{w}}{e} X \quad (19)$$

where $(K_c)_{air}$ is the collisional part of air kerma, K_{air} is the total air kerma and g is the fraction of initial kinetic energy of electrons radiated as bremsstrahlung.

The amount of energy lost to bremsstrahlung photons is not included in exposure because exposure is a measure of ionization finally produced by the secondary electrons. So the total kerma includes the fraction g radiates as bremsstrahlung. In any event, f is a small value. For ^{60}Co , $g = 0.003$; for ^{137}Cs , $g = 0.002$; and for orthovoltage $g \approx 0.0$.

The numerical relationship between air kerma and exposure for ^{60}Co is:

$$\begin{aligned} (1-0.003) K_{air} (\text{J/kg}) &= 33.97 (\text{J/C}) X (\text{C/kg}) \\ 0.997 K_{air} (\text{Gy}) &= 33.97 \times 2.58 \times 10^{-4} X (\text{R}) \\ 0.997 K_{air} (\text{Gy}) &= 8.76 \times 10^{-3} X (\text{R}) \\ K_{air} (\text{Gy}) &= 8.79 \times 10^{-3} X (\text{R}) \end{aligned}$$

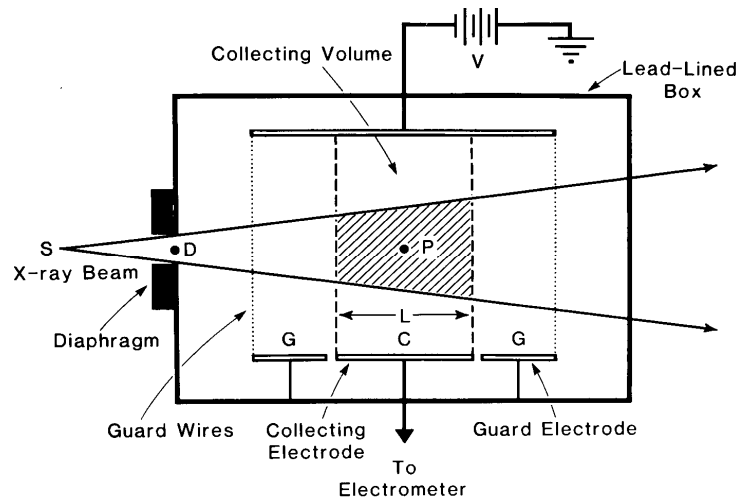
Similarly we may show that for ^{137}Cs gamma rays we have

$$K_{air} (\text{Gy}) = 8.78 \times 10^{-3} X (\text{R})$$

and for orthovoltage x-rays and lower energy x-rays we have

$$K_{air} (\text{Gy}) = 8.76 \times 10^{-3} X (\text{R})$$

Measurement of Exposure



A schematic diagram of a free-air chamber.

$$X_D = \frac{Q}{\rho A_D L} \quad (20)$$

In a free-air chamber, ionization is collected from the volume between the dotted lines. This collecting volume must be far enough removed from the diaphragm so that electronic equilibrium will be established. This distance must be greater than the maximum range of secondary electrons created. The plate separation must be twice this distance. Under these conditions electrons generated in the beam will expand all their energy before striking the collector.

The definition of the Roentgen is in terms of mass of air. The use of the term air implies what some have termed 'dry air'. Humidified air is a mixture of components of air and water vapor. Correction factors must be applied for measurement conditions other than those of the definition. At normal operating temperature and pressure the perfect gas law may be used. If the mass of air in the definition is taken as a unit mass, then the number of units in a volume V of 'dry air' is

$$\frac{273.2}{T} \frac{PV}{760}$$

Because of difference in W values and electron densities between air and water vapor a correction must be applied for humid air. In this case the number of unit masses of volume V is

$$\frac{273.2}{T} \frac{(P - 0.238 P_1)V}{760} \quad (21)$$

where, P_1 is the vapor pressure of moisture in the air in mm of mercury.

The collection volume is defined by the entrance aperture and the length of the collecting electrode. If the cross sectional area of the x-ray beam is A_d at point P inside the chamber then the exposure at that point is

$$X_d = \frac{Q}{\rho A_d L} \quad (22)$$

with Q = collected charge
 ρ = density of air
 L = length of collecting electrode

The exposure at the end entrance diaphragm is

$$X_D = \frac{Q}{\rho A_d L} \left(\frac{S_2}{S_1} \right)^2 \quad (23)$$

with S₂ = distance from source to point P inside chamber.
 S₁ = distance from source to entrance diaphragm D

Now the area of the entrance diaphragm is equal to A_d times an inverse square factor, i.e.

$$A_d = A_D \left(\frac{S_2}{S_1} \right)^2 \quad (24)$$

with A_D = area of entrance diaphragm. Then

$$X_D = \frac{Q}{\rho A_D \left(\frac{S_2}{S_1} \right)^2 L} \left(\frac{S_2}{S_1} \right)^2 \quad (25)$$

or

$$X_D = \frac{Q}{\rho A_D L} \quad (26)$$

This relation tells us that the exposure at the entrance diaphragm is equal to the charge collected from the free-air chamber decided by the product of air density, the area of the entrance diaphragm, and the length of the collecting electrode.

Cavity chambers

The basis of an air-wall chamber is that the air surrounding the active volume can be "condensed" into a "solid air" wall. A wall thick enough to provide electronic equilibrium permits measurement of the Roentgen with cavity chambers. The definition of an air-wall chamber is a chamber whose walls interact with radiation in the same manner as air interacts.

This condition means that the mass energy absorption and mass attenuation coefficients for the material should be the same as for air.

To ensure that the walls are equilibrium thickness and to correct for wall attenuation, measurements must be made for a number of wall thicknesses. If the first wall thickness is less than equilibrium thickness then as the thickness increases the signal will increase until the equilibrium thickness is reached. The signal will decrease with increasing wall thickness because of absorption of the primary photon beam in the wall. The exposure corrected for wall attenuation is found by extrapolating the attenuation curve back to zero wall thickness.

The use of cavity chambers to measure exposure is based on the Bragg-Gray relation. Basically the Bragg-Gray theory relates the energy absorbed in a medium to energy absorbed in a cavity in that medium. Equation (27) below considers the medium to be material “w” and the cavity to contain a gas “g”. The energy absorbed in the gas is equal to the number of ion pairs (or ionization) per unit mass of the gas times the average energy to create the ion pair. The energy per unit mass, absorbed dose is

$$D_w = J_g \left(\frac{\overline{W}}{e} \right) \left(\frac{S}{\rho} \right)_g^w \quad (27)$$

where D_w = absorbed dose in material w.

$\left(\frac{S}{\rho} \right)_g^w$ is the ratio of the mass stopping power of the electrons in material w to that in the gas g.

J_g is the ionization charge of one sign produced per unit mass of the cavity gas.

$\left(\frac{\overline{W}}{e} \right)$ is average energy absorbed per unit charge of ionization produced.

In an exposure measurement the medium w is the wall of the chamber when the wall is thick enough to provide electronic equilibrium. If the chamber wall is carbon then the absorbed dose in air in the absence of the chamber is

$$D_{air} = D_c \left(\frac{\mu_{en}}{\rho} \right)_c^{air} \quad (28)$$

D_c is the absorbed dose in carbon.

$\left(\frac{\mu_{en}}{\rho} \right)_c^{air}$ is the ratio of the mass energy absorption coefficient air to carbon.

Combining the two equations yields

$$D_{air} = J_g \left(\frac{\overline{W}}{e} \right) \left(\frac{S}{\rho} \right)_g^w \left(\frac{\mu_{en}}{\rho} \right)_c^{air} \quad (29)$$

If air is the cavity gas then the "g" may be replaced by "air" in all places in the equation. The current definition of the Roentgen is 2.58×10^{-4} Coulomb per kilogram of air. The above equation can be rewritten in terms of exposure as

$$\frac{D_{air}}{\left(\frac{W}{e}\right)} = X = \frac{1}{2.58 \times 10^{-4}} J_g \left(\frac{S}{\rho}\right)_g^w \left(\frac{\mu_{en}}{\rho}\right)_c^{air} \prod_i k_i \quad (30)$$

X = exposure in roentgens

$\prod_i k_i$ is the product of correction factors including stem scatter, recombination, wall thickness, and the correction that takes into account the mean center for electron production in the chamber wall.

Consider the relation between absorbed dose and exposure. One roentgen deposits energy in air to create ionization of

$$\mathbf{1 \text{ roentgen} = 2.58 \times 10^{-4} \text{ C/kg of air}}$$

The presently accepted value for $(W/e)_{air}$ is 33.97 joules/coulomb, which is defined as the average energy required to create an ion pair in air. Then

$$\begin{aligned} 1 \text{ roentgen} &= 2.58 \times 10^{-4} \text{ coulomb/kg of air} \times 33.97 \text{ joules/ coulomb} \\ &= 8.76 \times 10^{-3} \text{ joules /kg of air} \\ &= 0.876 \text{ cGy for air} \end{aligned}$$

In S.I. units $1\text{C/kg exposure} = 1\text{C/kg} \times 33.97 \text{ J/C} = 33.97 \text{ J/kg}$. Therefore, air exposed to 1 roentgen receives 0.876 cGy and air exposed to 1C/kg receives 33.97 Gy.

If some other material is exposed to one roentgen the absorbed dose in the medium will be

$$D_{med} = D_{air} \left(\frac{\mu_{en}}{\rho}\right)_{air}^{med}$$

For an exposure of X roentgens

$$D_{med} = 0.876 \left(\frac{\mu_{en}}{\rho}\right)_{air}^{med} X \text{ cGy} \quad (31)$$

or for an exposure of C/kg

$$D_{med} = 33.97 \left(\frac{\mu_{en}}{\rho} \right)_{air}^{med} X \quad \text{Gy} \quad \text{The factor} \quad (32)$$

$$0.876 \left(\frac{\mu_{en}}{\rho} \right)_{air}^{med} \frac{cGy}{R} \quad (33)$$

or

$$33.97 \left(\frac{\mu_{en}}{\rho} \right)_{air}^{med} Gy \frac{kg}{c} \quad (34)$$

has been assigned a special terminology; it is called the f factor. The f factor is no longer used in modern dosimetry protocols.

For higher energy photon beams an additional factor is required. This factor is A_{eq} . This factor represents the attenuation of the primary photon beam in reaching D_{max} in the medium. The equation for determining dose, to a small mass of water large enough to establish electronic equilibrium, from an exposure measurement is $D = f X A_{eq}$ for cobalt 60, $f = 0.967$ and $A_{eq} = 0.989$.

Charged Particle Equilibrium

Charged particle equilibrium (CPE) exists for a volume V if each charged particle of a given type and energy leaving v is replaced by an identical particle entering.

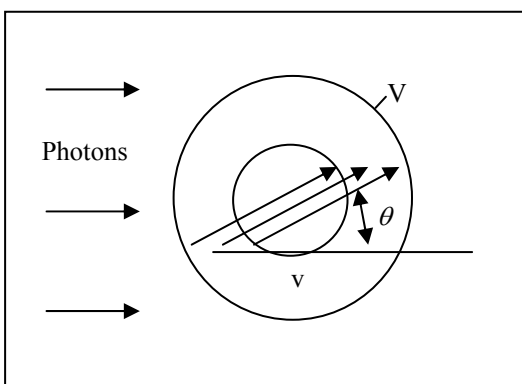
This definition applies in a statistical sense, and in what follows, all quantities will refer to expectation values.

Clearly, if there is CPE for a region, then

$$(R_{in})_c = (R_{out})_c \quad (35)$$

i.e. the energy carried in and out by charged particles is equal.

CPE for external photon sources



In the above, the large volume V contains a smaller one v . The boundaries of v and V are separated by at least the maximum distance of penetration of any secondary particles present. If the following conditions are satisfied throughout v , CPE will exist for the volume v .

1. The medium is homogeneous in density and composition
2. There exists a uniform field of photons (i.e. there is negligible attenuation);
3. No inhomogeneous electric or magnetic fields are present. It is not necessary that the secondary particles are isotropic as seen in the figure where all secondaries are created at angle θ .

If CPE holds, then equation (35) holds. Substituting this into equation (13) for the energy imparted, we get that for CPE

$$E \underline{\underline{CPE}} (R_{in})_u - (R_{out})_u + \Sigma Q \quad (36)$$

Substituting the definition for E_{tr} (equation 9), we find that for CPE:

$$E \underline{\underline{CPE}} E_{tr} + (R_{out})_u^{nonr} - (R_{out})_u \quad (37)$$

Equation 11 gives $E_{tr}^n = E_{tr} - R_u^r$ and hence for CPE we get.

$$E \underline{\underline{CPE}} E_{tr}^n + (R_{out})_u^{nonr} + R_u^r - (R_{out})_u \quad (38)$$

Recall:

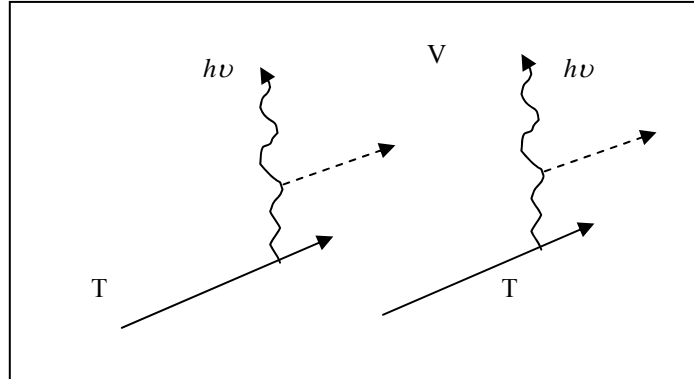
R_u^r : Radiative losses from particles originated in v ;

$(R_{out})_u^{nonr}$: energy of photons leaving v , except those that are radiative.

Under CPE conditions, the following equation holds as long as the volume V is small enough that all radiative-loss photons created in V can escape:

$$(R_{out})_u \underline{\underline{CPE}} (R_{out})_u^{nonr} + R_u^r \quad (39)$$

This equation states that the photon energy leaving V equals the sum of the energy of the non-radiative photons leaving V plus the energy lost radiatively by particles originating in V. The condition of CPE is needed to ensure that for every radiative loss contributing to R_u^r outside of V, there is a similar radiative event occurring inside V. The volume must then be small enough that the radiative photon gets out of V to be counted in $(R_{out})_u$.



In the above figure, as long as $h\nu_2$ escapes from V:

$$(R_{out})_u = h\nu_2$$

$$(R_{out})_u^{nonr} = 0$$

And on average, $h\nu_1 = h\nu_2$

$$R_u^r = h\nu_1$$

Hence question equation (39) is satisfied.

CPE, Dose and Collision Kerma

Under CPE conditions and for small enough volumes, substituting equation (39) into equation (38) gives:

$$\underline{\underline{E_{CPE}}} = E_{tr}^n$$

Shrink the volume gives:

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

i.e. under conditions of CPE at a point in a medium the absorbed dose is equal to the collision kerma there. This is true irrespective of radiative losses.

CPE: Dose and Kerma

The equality of K and K_c under conditions of CPE is very important because it relates a measurable quantity, the absorbed dose D , to a quantity we can calculate, the collision kerma.

$$K_c = \Psi \left(\frac{\mu_{en}}{\rho} \right)$$

Another aspect of this, which is used often in radiation dosimetry, is that it allows the ratio of the doses in two media, which are in the same photon fluence if conditions of CPE hold, to be calculated.

$$\frac{D_A}{D_B} = \frac{(K_c)_A}{(K_c)_B} = \frac{\left(\frac{\overline{\mu_{en}}}{\rho} \right)_A}{\left(\frac{\overline{\mu_{en}}}{\rho} \right)_B} = \left(\frac{\overline{\mu_{en}}}{\rho} \right)_B^A$$

Break Down of CPE

CPE does not exist in many situations in dosimetry. It is important to be aware if the theory being applied required CPE to hold (as it often does)

High-Energy Photon Beams

CPE can only occur after full buildup has been achieved. If the attenuation of the photon beam is significant in the distance traveled by electrons set in motion by the photons, then it is impossible for CPE to occur. For example a 10 MeV photon beam is attenuated 7% in the maximum range of its secondary electrons whereas a 1 MeV beam is only attenuated 1% in the corresponding distance.

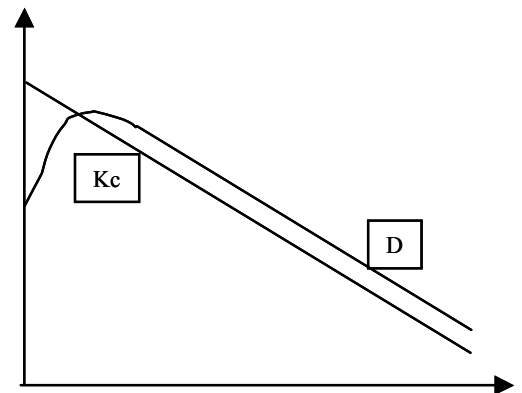
Transient Charged Particle Equilibrium (TCPE)

TCPE is said to exist at all points within a region in which the absorbed dose D is proportional to the collision kerma K_c .

Assume that radiative losses are negligible so that $K = K_c$. The kerma at the surface is K_0 and it attenuates with depth, but to a reasonable approximate it will be exponential with some effective attenuation coefficient.

The absorbed dose D is non-zero at the surface due to back-scattered electrons and photons. The dose curve increases as the charged particle fluence builds up and reaches a maximum at the point where the increase becomes balanced by the decrease due to attenuation of the photon beam. The dose maximum occurs at approximately the point where the D and K curve across.

At a distance beyond the maximum distance secondary charged particles starting at the surface can penetrate,



the D curve becomes parallel to the K curve and hence TCPE exists.

Roesch suggested the following relationship:

$$D \stackrel{TCPE}{=} K_c e^{\mu' \bar{x}}$$

$$\stackrel{TCPE}{=} K_c (1 + \mu' \bar{x})$$

$$= K_c \beta$$

where μ' is the effective attenuation coefficient and \bar{x} is the mean distance electrons transport their kinetic energy in the beam direction. β is the ratio of absorbed dose to collision kerma at a given depth, β is always greater than 1.

Cavity Theory

Large cavity theory (for "photon detectors"): If the detector size is much greater than the mean electron range in a phantom irradiated by a photon beam, then

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

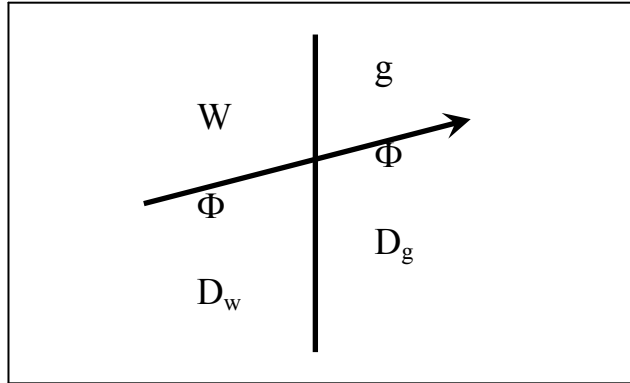
Small (Bragg-Gray) cavity theory (for "electron detectors"): if the detector size is much smaller than the mean electron range in a phantom irradiated by a photon beam, then

$$\frac{D_{med}}{D_{det}} = S_{med, det}$$

Burlin cavity theory: for intermediate sized detectors.

$$\frac{D_{med}}{D_{det}} = \alpha \left(\frac{\bar{\mu}_{en}}{\rho} \right)_{med, det} + (1 - \alpha) S_{med, det}$$

Bragg -Gray Cavity Theory



Consider a fluence Φ of charged particles of energy T crossing the interface between medium w and medium g immediately to each side of the boundary, the fluence must be the same, and

$$D_w = \Phi (S / \rho)_{col,w}$$

hence we can write:

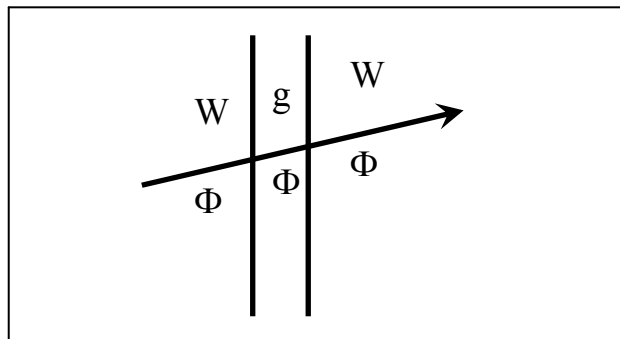
and

$$D_g = \Phi \left(\frac{S}{\rho} \right)_{col,g}$$

The ratio of absorbed doses is then:

$$\frac{D_w}{D_g} = \frac{\Phi(S / \rho)_{col,w}}{\Phi(S / \rho)_{col,g}}$$

Consider now a region of otherwise homogeneous medium w , which contains a thin layer, or cavity filled with another medium g (see below).



First Bragg-Gray Condition

The thickness of the g-layer is assumed to be so small in comparison with the range of charged particles striking it that its presence does not perturb the charged particle field.

Second Bragg-Gray Condition

The absorbed dose in the cavity is assumed to be deposited entirely by the charged particles crossing it. This condition is valid for gas filled cavities in high-energy photon beams but not for kV x-rays.

We define the spectrum-averaged collision stopping power in the cavity medium as:

$$\left(\frac{\bar{S}}{\rho}\right)_g = \frac{\int_0^{T_{\max}} \Phi T(S/\rho)_{col,g} dT}{\int_0^{T_{\max}} \Phi dT} = \frac{D_g}{\Phi}$$

And likewise, if we fill the cavity with a thin layer of wall material we would have

$$\left(\frac{\bar{S}}{\rho}\right)_w = \frac{\int_0^{T_{\max}} \Phi T(S/\rho)_{col,w} dT}{\int_0^{T_{\max}} \Phi dT} = \frac{D_w}{\Phi}$$

Combining these equations, we get the Bragg-Gray relationship in terms of the absorbed dose in the cavity, viz:

$$\frac{D_w}{D_g} = \frac{\left(\frac{\bar{S}}{\rho}\right)_w \Phi}{\left(\frac{\bar{S}}{\rho}\right)_g \Phi} = \left(\frac{\bar{S}}{\rho}\right)_g^w$$

If the cavity is filled with a gas in which a charge of Q is produced by the radiation, then we have, using the definition of W/e:

$$D_g = \frac{Q}{m} \left(\frac{W}{e}\right)_g$$

where D_g is in Gy, Q in c, m, the mass of the gas in kg and (W/e) is in J/C Finally we obtain the B-G relation expressed in terms of cavity ionization:

$$D_w = \frac{Q}{m} \left(\frac{W}{e}\right)_g \left(\frac{\bar{S}}{\rho}\right)_g^w$$

Note these equations make use of the unrestricted collision stopping powers. The effects of knock-on electrons are included in these stopping powers. The integration is over the energy fluence for primary electrons only.

Note that the theory requires CPE for at least the knock-on electrons, since this is required in order to use the relationship between dose, fluence, and stopping powers. If there is also CPE for the primary electron spectrum certain computational shortcuts are possible.

Spencer-Attix Theory

Considering the large number of knock-on electrons, it is surprising that Bragg-Gray works at all!

Spencer and Attix formulated a theory, which took these knock-on electrons into account, and actually developed a very complex procedure for evaluating their theory, assuming CPE held. This theory was in much better agreement with the experimental results and this has been an accepted procedure ever since. The theory still requires the two Bragg-Gray conditions to hold. In fact, S-A theory is more stringent because it assumes the entire secondary electron energy fluence is not disturbed by the cavity.

The basic idea of S-A theory is explicitly to take into account all knock-on electrons above some energy threshold (traditionally called Δ) and consider all other energy losses as local.

S-A theory considers the electron fluence, to include primaries and knock-ons with energies above Δ .

The integrals for the dose now start at Δ . Also rather than the unrestricted collision stopping power $(S/\rho)_{\text{col}}$ we now use the restricted stopping power $(L(\Delta)/\rho)$ which considers only energy losses creating electrons below Δ since the energy lost to higher energy electrons is explicitly accounted for by the presence of those electrons in the fluence.

In analogy with the B-G theory, the S-A equation is now usually written as:

$$\frac{D_m}{D_g} = \frac{\int_{\Delta}^{E_{\text{max}}} \Phi \left(\frac{L(\Delta)}{\rho} \right)_m dE + \text{TE}_m}{\int_{\Delta}^{E_{\text{max}}} \Phi \left(\frac{L(\Delta)}{\rho} \right)_g dE + \text{TE}_g} = \left(\frac{\bar{L}}{\rho} \right)_g^m$$

where TE is a term to account for the track-end effect.

Δ is traditionally taken as the energy of an electron whose range is equal to the mean path-length in the cavity. A more physical choice would be based on the mean energy needed for a

knock-on created in the cavity to escape from it. Fortunately, in practical situations, the theory is insensitive to the choice of Δ .

A value of 10 keV is often used for convenience. The csda range of 10 keV electrons in air is 2 mm.

The track end term takes into account the energy deposition by those particles whose energy falls below Δ . This represents a significant fraction of the energy deposition. Note that the term should be the same in both cases since the energy fluence is assumed to be the same in both cases. The TE term can be scored directly in a Monte Carlo calculation, or estimated by:

$$TE = \Phi(\Delta)(S(\Delta)/\rho)\Delta$$

where the product of the first two terms (viz the electron fluence, inferential in energy and the total mass collision stopping power, both evaluated at the cutoff Δ) is roughly equal to the number of stoppers per unit mass.

Spencer Attix cavity theory does not require CPE to apply, as long as the cavity does not disturb the electron fluence. This is because the effect of knock-on electrons is considered explicitly and the assumption of local energy deposition is accurate on its own without invoking CPE. S-A theory includes an explicit dependence, through the choice of Δ , on the cavity size.

Spencer-Attix vs Bragg-Gray

Water to air stopping power ratios at 0.65 of csda range (Nahum 1978).

Incident Energy (MeV)	Stopping power ratio of water to air			
	Spencer-Attix Δ (MeV)			Bragg-Gray
	0.001	0.01	0.1	
5	1.146	1.131	1.124	1.121
10	1.116	1.102	1.096	1.091
20	1.076	1.064	1.058	1.053

The effects are much more dramatic for high-Z materials, but then the accuracy of the basic principles are in questions too.

Kilovoltage X-Ray Calibration (TG-61)

Absorbed dose determination for low-energy x-rays (under 150 kV)

The in-air method:

$$D_w = MN_K P_{stem,air} B_w \left(\frac{\bar{\mu}_{en}}{\rho} \right)_{air}^w$$

where

M is the free-in-air chamber reading corrected for temperature, pressure, polarity effect and electrometer accuracy

N_K the air-kerma calibration factor

B_w the phantom backscatter factor

$P_{stem,air}$ the chamber stem correction factor

$\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{air}^w$ the ratio for water-to-air of the mass energy-absorption coefficients

Absorbed dose determination for medium-energy x-rays (100-300 kV)

The in-phantom method:

$$D_w = MN_K P_{Q,chan} P_{sheath} \left(\frac{\bar{\mu}_{en}}{\rho} \right)_{air}^w$$

where

M is the chamber reading corrected for temperature, pressure, polarity effect and electrometer accuracy

N_K the air-kerma calibration factor

$P_{Q,chan}$ is the overall chamber correction factor

P_{sheath} is the waterproofing sleeve correction factor

$\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{air}^w$ the ratio for water-to-air of the mass energy-absorption coefficients

Note: the in-air method may also be used for medium-energy x-rays.

Megavoltage Photon & Electron Calibration (TG-51)

1. The AAPM TG-51 protocol applies to clinical *reference dosimetry* for *external beam* radiation therapy using *ion chambers*.
2. Beam quality range: ⁶⁰Co – 50 MV for photons
 4 – 50 MeV for electrons
3. A *water* phantom (at least 30 cm x 30 cm x 30 cm) must be used for clinical reference dosimetry. Other phantom materials may be used for routine checks and relative dosimetry measurements.
4. Simplification compared to TG-21 protocol (less tabulated data).

TG-21:

$$D_w = \overline{M} P_{ion} C_{cap} \left(\frac{\overline{L}}{\rho} \right)_{air}^w P_{wall} P_{repl} N_{gas}$$

TG-51:

$$D_w^Q = M k_Q N_{D,w}^{60Co}$$

for photons:

$$D_w^Q = M_{raw} P_{ion} P_{TP} P_{elec} P_{pol} k_Q N_{D,w}^{60Co}$$

for electrons:

$$D_w^Q = M_{raw} P_{TP} P_{pol} P_{ion} P_{elec} k'_{R50} k_{ecal} P_{gr}^Q N_{D,w}^{60Co}$$

5. Improved accuracy on dose to water at reference depth.
6. Worksheets for various situations are presented.
7. A list of equipment required is given.

Equipment needed

1. Ion chamber and electrometer (calibration traceable to national standards laboratories).
2. Equipment for two independent checks.
3. Voltage supply (two voltages, both signs)
4. Waterproofing for ion chamber (if needed): < 1 mm PMMA
5. Water phantom: at least 30cm x 30cm x 30cm
6. Lead foil for photons 10 MV and above: 1 mm \pm 20%
7. System to measure temperature and pressure

Beam Specification

Electron beam specification: R_{50}

R_{50} : the depth in water at which the absorbed dose falls to 50% of the maximum dose.

Field size at 100cm SSD: 10cm x 10cm for $R_{50} \leq 8.5$ cm ($E \leq 20$ MeV)
20cm x 20cm for $R_{50} > 8.5$ cm ($E > 20$ MeV)

I_{50} : the depth in water at which the measured ionization falls to 50% of the maximum ionization.

The electron beam quality specifier R_{50} is determined from I_{50} using

$$R_{50} = 1.029I_{50} - 0.06 \text{ (cm)}$$

for $2\text{cm} \leq I_{50} \leq 10\text{cm}$

or

$$R_{50} = 1.059I_{50} - 0.37 \text{ (cm)}$$

for $I_{50} > 10\text{cm}$

Other alternatives:

- Using a good quality diode detector
- Convert depth ionization to depth dose

Photon beam specification: %dd(10)_x

%dd(10): the measured percentage depth dose at 10 cm depth in water irradiated by a 10 cm x 10 cm field defined at 100 cm SSD.

%dd(10)_x: the photon component of the percentage depth dose at 10 cm depth in water irradiated by a 10 cm x 10 cm field defined at 100 cm SSD.

%dd(10)_{pb}: the percentage depth dose at 10 cm depth in water irradiated by a 10 cm x 10 cm field defined at 100 cm SSD with a 1 mm lead foil in place below the accelerator at about 50 (±5) cm from the phantom surface (or 30±1 cm if 50 cm clearance is not available).

For photon energies below 10 MV

$$\%dd(10)_x = \%dd(10)$$

For photon energies above 10 MV

$$\%dd(10)_x = [0.8905 + 0.00150\%dd(10)_{pb}] \%dd(10)_{pb}$$

for foil at 50 cm and %dd(10)_{pb} ≥ 73%

or

$$\%dd(10)_x = [0.8116 + 0.00264\%dd(10)_{pb}] \%dd(10)_{pb}$$

for foil at 30 cm and %dd(10)_{pb} ≥ 71%

Otherwise

$$\%dd(10)_x = \%dd(10)_{pb}$$

A general formula using %dd(10) measured for an open beam:

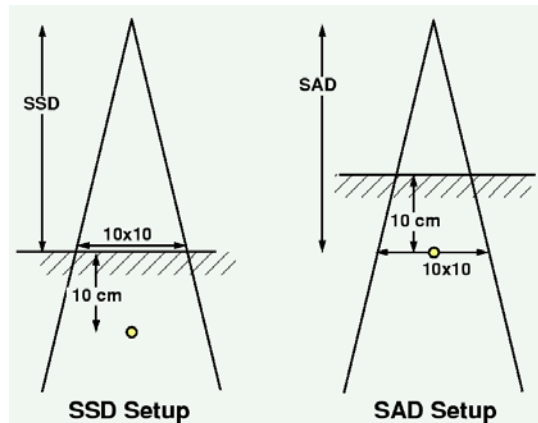
$$\%dd(10)_x = 1.267\%dd(10) - 20.0$$

for 75% < %dd(10) ≤ 89%

Reference Conditions

Photon beam measurements

The reference depth: $d_{\text{ref}} = 10 \text{ cm}$ depth in water irradiated by a $10\text{cm} \times 10\text{cm}$ field defined at 100cm SSD or SAD.

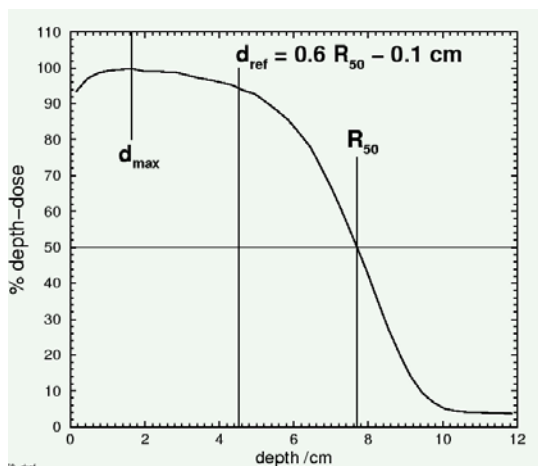


Electron beam measurements

The reference depth: $d_{\text{ref}} = 0.6 R_{50} - 0.1 \text{ cm}$ depth in water.

The field size: a $10\text{cm} \times 10\text{cm}$ field for $d_{\text{ref}} \leq 8.5\text{cm}$ ($E \leq 20 \text{ MeV}$)
a $20\text{cm} \times 20\text{cm}$ field for $d_{\text{ref}} > 8.5\text{cm}$ ($E > 20 \text{ MeV}$)

SSD = 90-110cm are allowed.

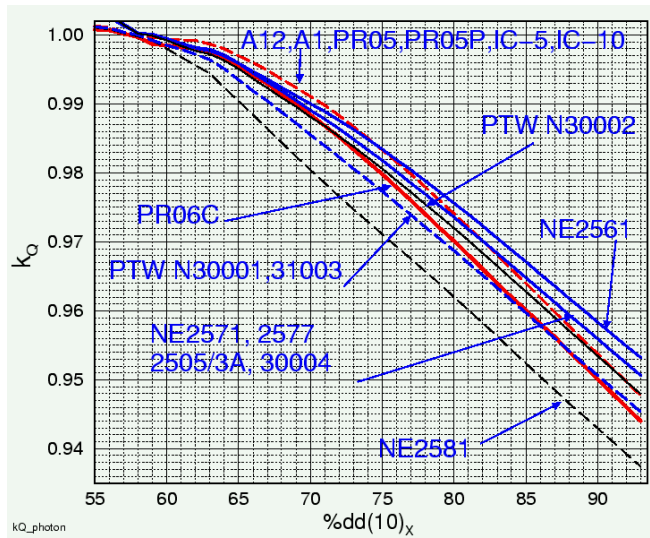


Step-by-Step Procedure to Determine D_w in a Photon Beam

1. Obtain a traceable $N_{D,w}^{60Co}$ for the ion chamber.
2. Measure $\%dd(10)_{pb}$ with a lead foil.
3. Deduce $\%dd(10)_x$ from $\%dd(10)_{pb}$ for an open beam.
4. Measure M_{raw} at 10 cm depth in water with a 10cm x 10cm field defined at 100 SSD or SAD.
5. $M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$.
6. Look up k_Q (Table I or Figure 4 in TG-51 report) for the chamber.
7. Finally, $D_w^Q = M k_Q N_{D,w}^{60Co}$ (Gy)
8. Derive dose at other depths using PDD, TPR or TMR.

Step-by-Step Procedure to Determine D_w in an Electron Beam

1. Obtain a traceable $N_{D,w}^{60Co}$ for the ion chamber
2. Measure I_{50} to derive R_{50} .
3. Deduce reference depth $d_{ref} = 0.6 R_{50} - 0.1$ cm
4. Measure M_{raw} at d_{ref} in water with a 10cm x 10cm (or 20cm x 20cm if $R_{50} > 8.5$ cm) field defined at 100 SSD
5. $M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$
6. Look up k_{ecal} (Table II or Table III in TG-51 report) for the chamber.
7. Determine $k'_{R_{50}}$ (Figures 5-8, Eqs. 19-20)
8. Establish P_{gr}^Q (Eq. 21, M_{raw} at two depths)
9. Finally, $D_w^Q = M P_{gr}^Q k'_{R_{50}} k_{ecal} N_{D,w}^{60Co}$ (Gy)
10. Derive dose at other depths using PDD.



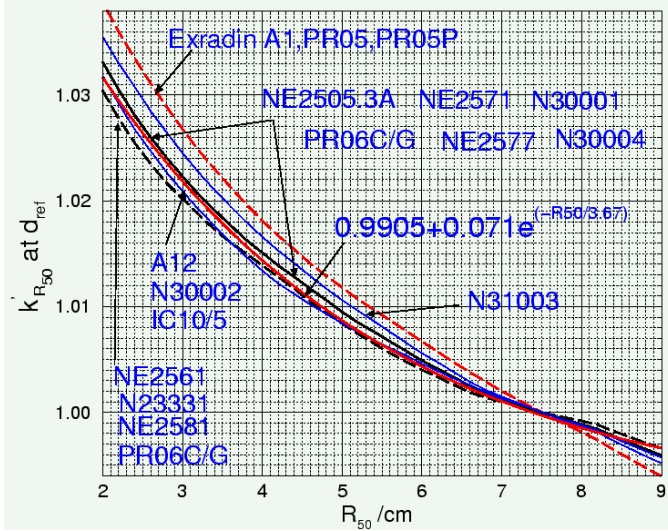
AAPM Fig. 4

Values of the photon-electron conversion factor k_{ecal} for plain-parallel chambers at $R_{50} = 7.5\text{cm}$ (TG-51 Table II)

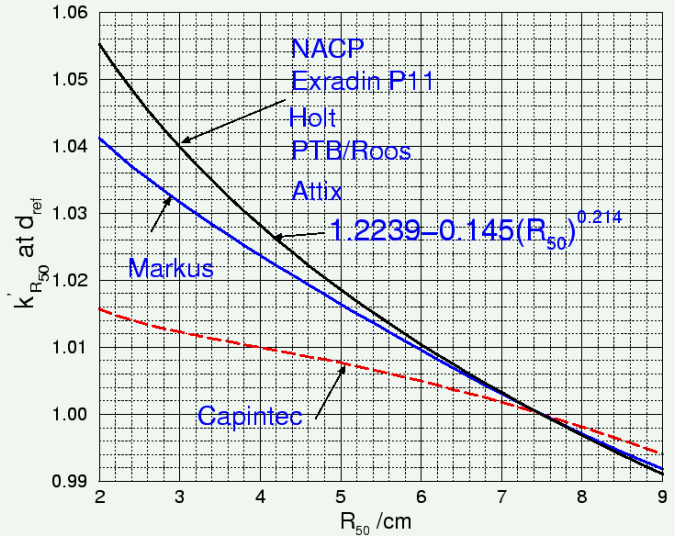
Chamber	k_{ecal}
Attix	0.883
Capintec	0.921
PTB/Roos	0.901
Exradin	0.888
Holt	0.900
Markus	0.905
NACP	0.888

Values of the photon-electron conversion factor k_{ecal} for cylindrical chambers at $R_{50} = 7.5\text{cm}$ (TG-51 Table III, incomplete)

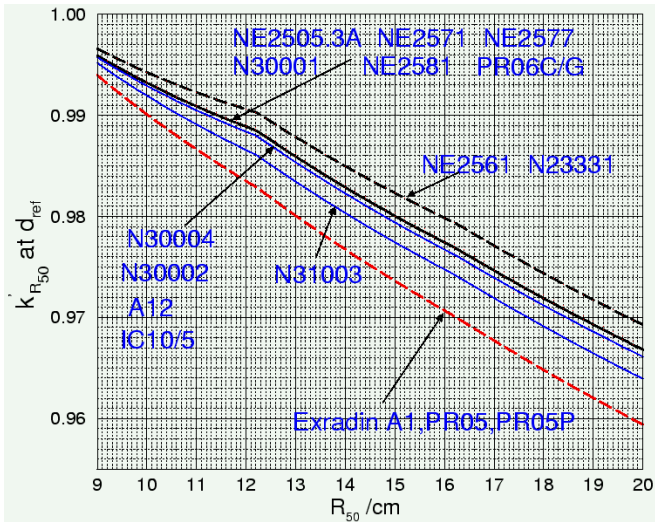
Chamber	k_{ecal}
NE2571	0.903
NE2561	0.904
NE2581	0.885
Capintec PR-06C/G	0.900
PTW N30001	0.897
PTW N23331	0.896
Exradin A12	0.906
Wellhofer IC-10/IC-5	0.904



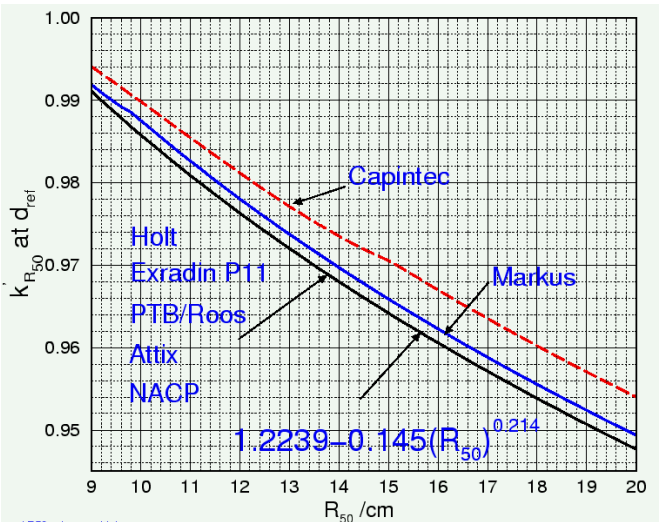
AAPM Fig. 5



AAPM Fig. 6



AAPM Fig. 7



AAPM Fig. 8

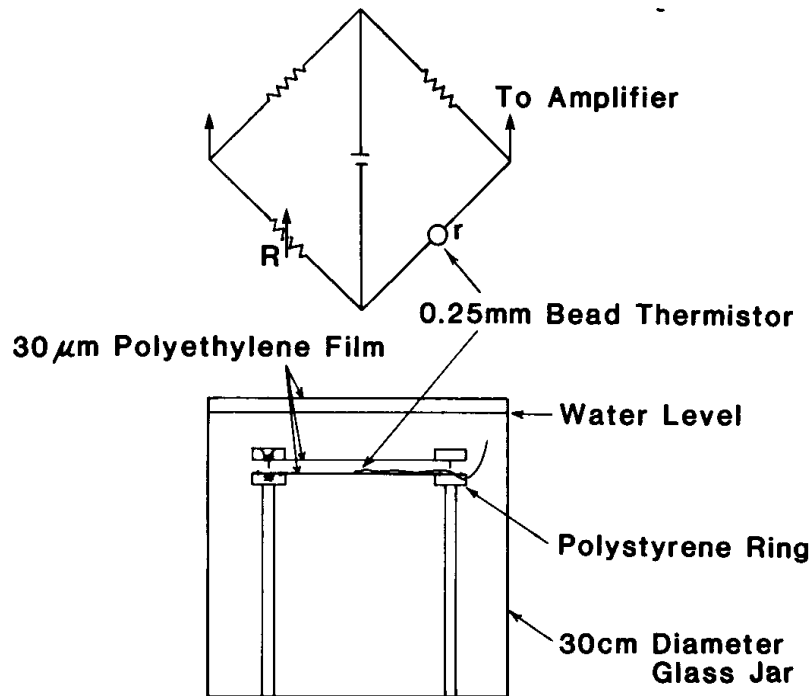
Measurement of Absorbed Dose

Calorimetry

Since the specific heat of water is $1 \text{ cal/g}^\circ\text{C}$ or $10^3 \text{ cal/kg}^\circ\text{C}$ and $1 \text{ cal} = 4.185 \text{ J}$, the rise in temperature, ΔT produced by 1 Gy is

$$\Delta T = \frac{1}{4.185} (\text{cal} / \text{kg}^{-1}) \times \frac{1}{10^3} (\text{cal}^{-1} \text{kg}^\circ\text{C}) = 2.389 \times 10^{-4} \text{ }^\circ\text{C}$$

To measure this temperature rise with 1% precision would require a thermometer capable of detecting temperature changes of the order of $2 \mu^\circ\text{C}$.



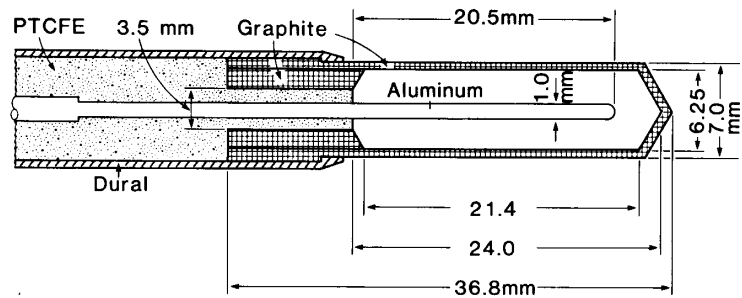
Schematic diagram of Domen's calorimeter

Ionization Chamber Dosimetry

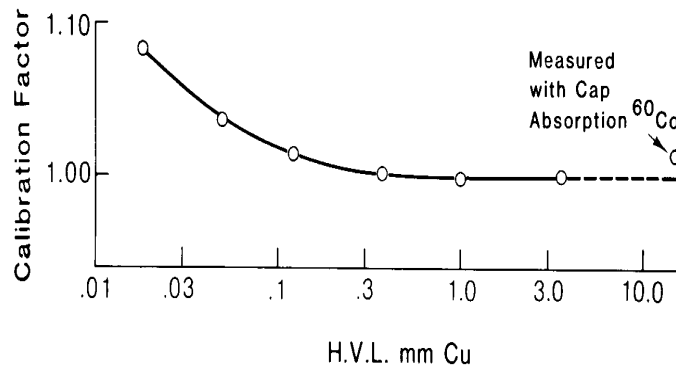
Desirable chamber characteristics

- "flat" energy response
- "flat" angular response
- minimal stem leakage
- minimal polarity effect
- minimal ion recombination losses
- high sensitivity
- small dimensions in the measurement direction

Thimble Chambers

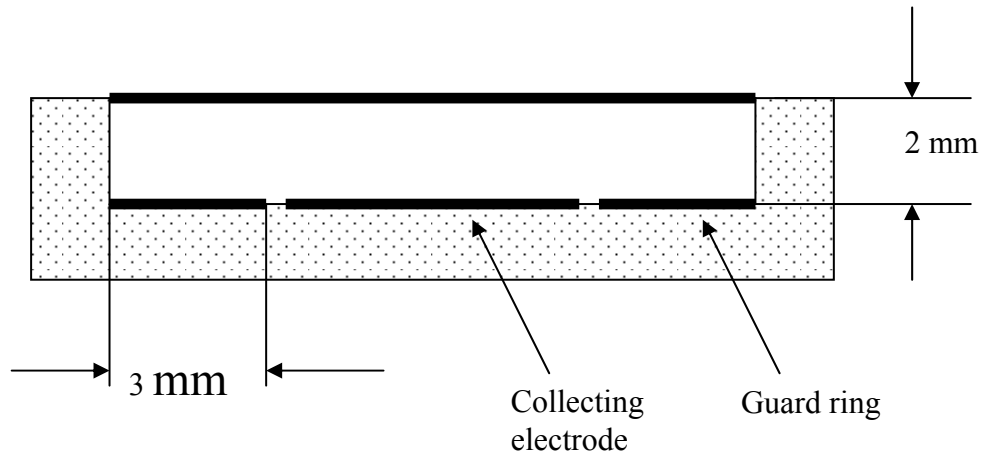


Schematic diagram of a Farmer chamber. The thimble wall is made of graphite and the central electrode is made of aluminum. The collecting volume of the chamber is nominally 0.6 cm³.



Energy response of a typical Farmer chamber.

Parallel-Plate Chambers



A parallel-plate chamber usually has a thin front wall (window) and small electrode spacing. These features are important for surface dose measurement and to minimize cavity perturbations in the radiation field. The 3-mm guard ring width is important to minimize the in-scatter effect in an electron beam. The Markus chamber has a smaller guard ring and requires a perturbation correction factor that deviates from unity by several percent at low electron energies (< 10 MeV) because of the electron in-scatter effect.

Charge Measurement

According to AAPM TG-51 protocol:

$$M = P_{ion} P_{TP} P_{elec} P_{pol} M_{raw}$$

where

M is the fully corrected ion chamber reading.

M_{raw} is the uncorrected ion chamber reading.

P_{pol} is the polarity correction factor

$$P_{pol} = \left| \frac{(M_{raw}^+ - M_{raw}^-)}{2 M_{raw}} \right|$$

P_{elec} is the electrometer correction factor (from an ADCL)

P_{TP} is the temperature-pressure correction factor

$$P_{TP} = \frac{273.2 + T}{273.2 + 22.0} \times \frac{101.33}{P}$$

P_{ion} is the recombination correction factor (see below)

The P_{ion} Factor

In an ion chamber, some electrons and positive ions recombine prior to being swept from the chamber and measured as part of the charge.

P_{ion} varies with dose rate, chamber geometry and collection voltage. P_{ion} must be established for each calibration situation.

TG-51 protocol recommended using the standard two-voltage techniques for determining P_{ion} . Let V_H is the normal operating voltage for the ion chamber and the M_{raw}^H is the chamber reading at V_H . After measuring M_{raw}^H , reduce the voltage to by at least a factor of 2 to V_L and measure M_{raw}^L .

For continuous beams (i.e., ^{60}Co)

$$P_{ion} = \frac{1 - (V_H / V_L)^2}{M_{raw}^H / M_{raw}^L - (V_H / V_L)^2}$$

For pulsed or pulsed-swept beams

$$P_{ion} = \frac{1 - (V_H / V_L)}{M_{raw}^H / M_{raw}^L - (V_H / V_L)}$$

If it is found that $P_{ion} > 1.05$, then the AAPM TG-51 protocol strongly recommends that a different chamber be used so that P_{ion} is reduced. Voltages should not be increased above normal operating voltages just to reduce P_{ion} since there are indications in the literature that the assumptions in the standard theories break down at higher voltages.

Chemical Dosimetry

The energy absorbed from ionization radiation may produce a chemical change and if this change can be determined, it can be used as a measure of absorbed dose. Many systems of chemical dosimetry have been proposed but the ferrous sulfate or the Fricke dosimeter is considered to be the most developed system for the precision measurement of absorbed dose.

Ferrous Sulfate (Fricke) Dosimeter

The Fricke solution consists of 0.001 mole/liter ferrous sulfate or ferrous ammonium sulfate, 0.001 mole/liter NaCl, and 0.4 mole/liter sulfuric acid. The reason for NaCl in the solution is to counteract the effects of organic impurities present despite all the necessary precautions. When the solution is irradiated, the ferrous ions, Fe^{2+} , are oxidized by radiation to ferric ions, Fe^{3+} . The ferric ion concentration is determined in the ultraviolet light at wavelength of 224 and 304 nm. The Fricke solution is usually contained in plastic or glass vessels, which may have an effect on the dose measured by the Fricke solution due to the difference in photon attenuation and electron scattering.

The Radiation Chemical Yield

ICRU defines the radiation chemical yield $G(X)$ as the change in molar concentration per unit energy absorbed by the solution (in mole/J). The radiation chemical yield has traditionally been measured in terms of the number of molecules produced per 100 eV energy absorbed. This number is known as the G-value. $G(X)$ can be derived from the G-value by multiplying it by 1.037×10^{-7} . The average dose in the solution is given by

$$D = \frac{\Delta M}{\rho G(X)} (\text{Gy})$$

where ΔM is the change in molar concentration (mole/liter) and ρ is the solution density (kg/liter). The G-value for Fricke dosimetry has been determined by many investigators. The table below gives the value recommended by ICRU report 14 for photons from ^{137}Cs to 30 MV. A constant G-value of $15.7 \pm 0.6/100\text{eV}$ is recommended for electrons in the energy range of 1 to 30 MeV for 0.4 mole/liter H_2SO_4 dosimetry solution.

Recommended G-values for the ferrous sulfate dosimeter (0.4 mole/liter H_2SO_4) for photon beams.

Radiation	G Value (No./100 eV)
^{137}Cs	15.3 ± 0.3
^{137}Cs	15.4 ± 0.3
^{60}Co	15.5 ± 0.2
4 MV	15.5 ± 0.3
5 - 10 MV	15.6 ± 0.4
11 - 30 MV	15.7 ± 0.6

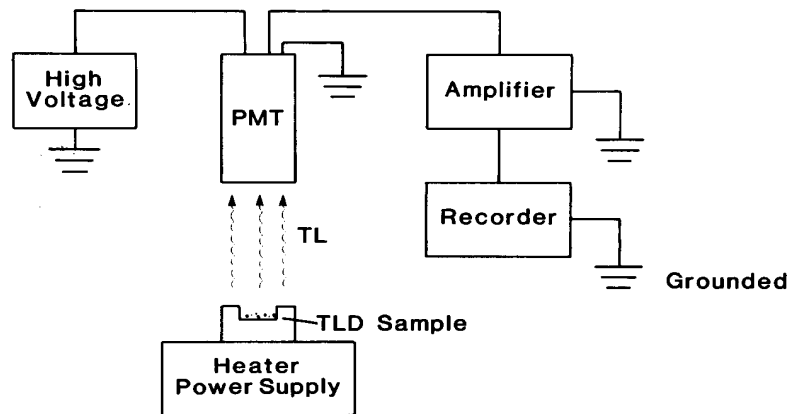
Data from ICRU Report 14 (Bethesda, MD: ICRU, 1969)

Solid State Methods

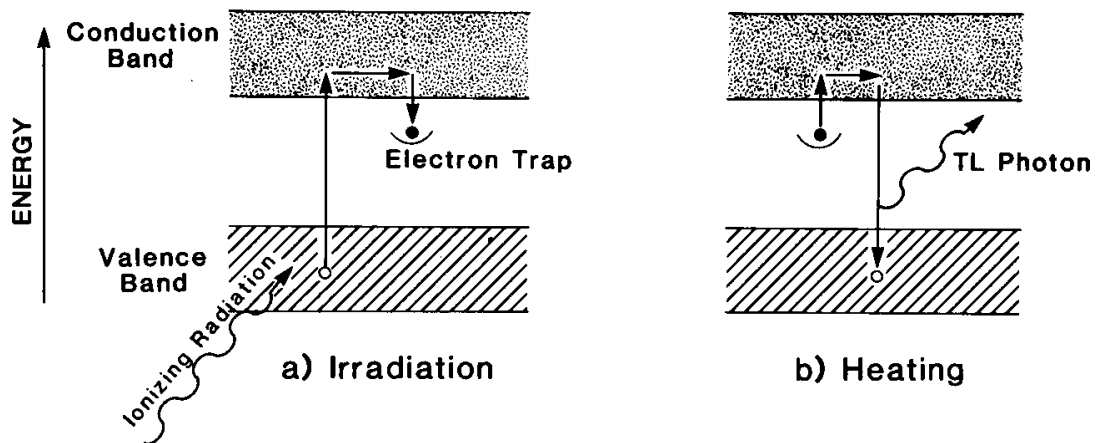
Thermoluminescence dosimeters

Many crystalline materials show properties of thermoluminescence (TL). When such a crystal is irradiated, a very minute fraction of the absorbed energy is stored in the crystal lattice. Some of the energy can be recovered later as visible light if the material is heated. This phenomenon of the release of visible photons by thermal means is known as thermoluminescence.

The figure below shows how the TL output may be measured. The irradiated material is placed in a heater cup or planchette where it is heated for a reproducible heating cycle. The emitted light is measured by a photomultiplier tube (PMT), which converts light into an electrical current. The current is then amplified and measured by a recorder or a counter.



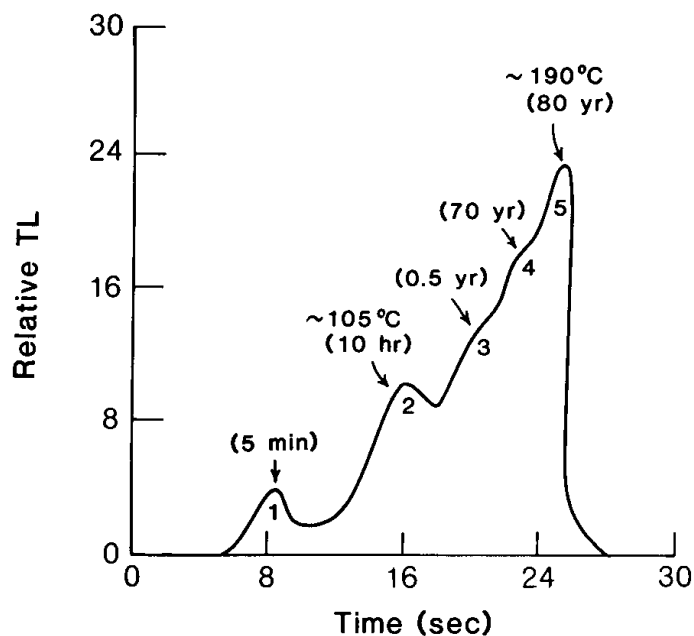
Schematic diagram showing apparatus for measuring thermoluminescence.



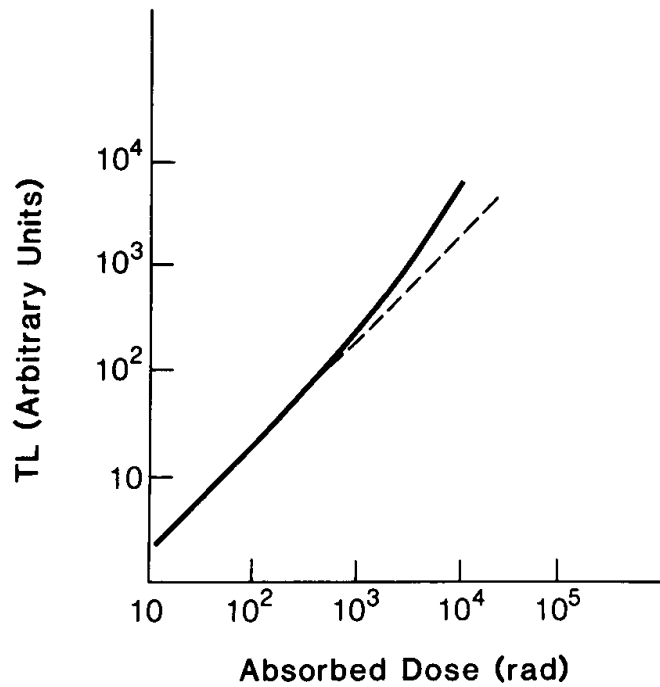
A simplified energy level diagram to illustrate thermoluminescence process.

Characteristics of Various Phosphors.

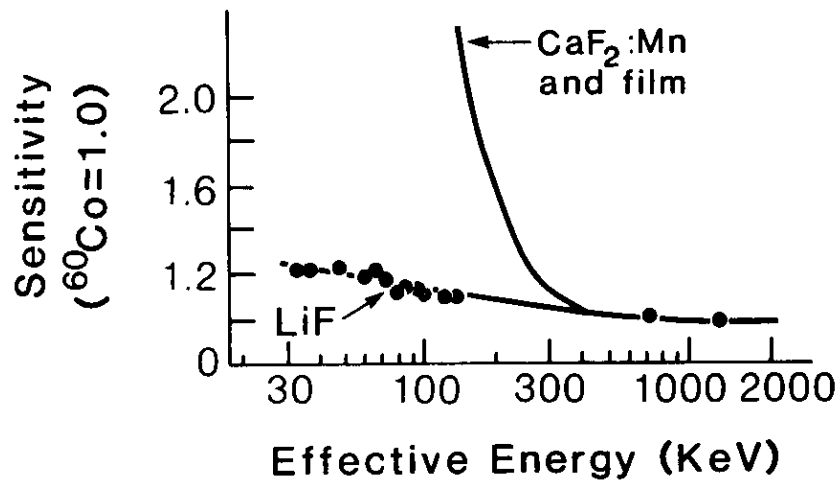
Characteristic	LiF	Li ₂ B ₄ O ₇ :Mn	CaF ₂ :Mn	CaF ₂ :nat	CaSO ₄ :Mn
Density (g/cc)	2.64	2.3	3.18	3.18	2.61
Effective atomic no.	8.2	7.4	16.3	16.3	15.3
TL emission spectra (Å)					
Range	3500–6000	5300–6300	4400–6000	3500–5000	4500–6000
Maximum	4000	6050	5000	3800	5000
Temperature of main TL glow peak	195°C	200°C	260°C	260°C	110°C
Efficiency at cobalt-60 (relative to LiF)	1.0	0.3	3	23	70
Energy response without added filter (30 keV/cobalt-60)	1.25	0.9	13	13	10
Useful range	Small, <5%/12 weeks	mR–10 ⁶ R	mR–3 × 10 ⁵ R	mR–10 ⁴ R	R–10 ⁴ R
Fading	mR–10 ⁵ R	10% in first month	10% in first month	No detectable fading	50–60% in the first 24 hours
Light sensitivity	Essentially none	Essentially none	Essentially none	Yes	Yes
Physical form	Powder, extruded, Teflon-embedded, silicon-embedded, glass capillaries	Powder, Teflon-embedded	Powder, Teflon-embedded, hot-pressed chips, glass capillaries	Special dosimeters	Powder, Teflon-embedded



An example of glowing curve of LiF (TLD-100) after phosphor has been annealed at 400 °C for 1 h and read immediately after irradiation to 100 R.



An example of TL vs. absorbed dose curve for TLD-100 power (schematic).

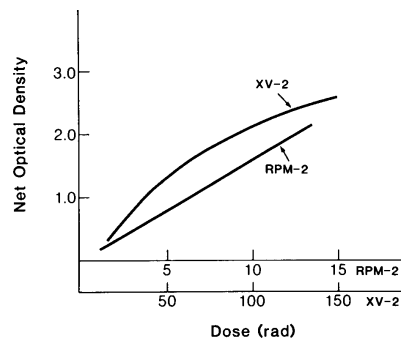


Energy response curve for LiF (TLD-100), CaF₂:Mn and a photographic film.

Film Dosimetry

Film is often used for relative dose measurement. A radiographic film consists of a transparent film base (cellulose acetate or polyester resin) coated with an emulsion containing very small crystals of silver bromide. When the film is exposed to ionizing radiation or visible light, a chemical change takes place within the exposed crystals to form small grains of metallic silver. The film is then fixed. The unaffected granules are removed by the fixing solution, leaving a clear film in their place. The metallic silver, which is not affected by the fixing process, causes darkening of the film. Thus the degree of darkening of an area of the film depends on the amount of free silver deposited and, consequently, on the radiation energy absorbed. The degree of blackening of the film is measured by determining optical density with a densitometer. This instrument consists of a light source, a small aperture through which the light is directed and a light detector (photocell) to measure the light intensity transmitted through the film. The optical density OD, is defined as

$$OD = \log \frac{I_0}{I}$$



Sensitometric curve of Kodak XV-2 film and Kodak RPM-2 (Type M) film.

Semiconductor detectors

Semiconductor detectors have characteristics that make them very attractive as dosimeters, for measuring either dose or dose rate, as a substitute for an ion chamber. They can also serve as a solid-state analogue of a proportional counter, since the ionization produced by a charged particle traversing the sensitive volume of the detector is proportional to the energy spent, irrespective of LET, for particles lighter than α 's. Some internal amplification is even possible in the "avalanche detector" mode of operation, but external amplification is usually preferred. The LET-independence is an advantage over scintillation detectors, allowing simpler interpretation of pulse heights in terms of energy imparted. Silicon diode detectors are often used for relative dose measurement.

In a totally different method of application, semiconductor detectors may be employed as neutron dosimeters by measuring the resulting radiation damage done by the neutrons.

Sample Questions

- Can you describe the depth-dose/kerma curves and their differences?
- What's the difference between kV and MV dosimetry?
- What's the difference between TG-21 and TG-51?
- What's the physical meaning of the k_Q factor in TG-51?
- Can you describe the equipment need for MV photon and electron reference dosimetry?
- Can you describe the step-by-step procedure to Determine D_w in a photon beam?
- Can you describe the step-by-step procedure to Determine D_w in an electron beam?
- What's the difference in characteristics and usage between a cylindrical chamber and a parallel-plate chamber?
- Can you describe the geometry of a well designed cylindrical or parallel-plate chamber?
- Can you explain the ion recombination effect and the polarity effect? Are they more significant in a Co-60 beam, a linac electron beam or a linac photon beam?
- What's chemical dosimetry? Can you describe Fricke dosimetry?
- What kind of solid detectors are commonly used for radiotherapy dosimetry?
- Can you describe how film, diode or TLD works? Can they be used for absolute dosimetry or relative dosimetry? What are their measurement uncertainties?

Educational Objectives

The educational objectives are (1) to review radiation quantities and their use in radiation measurement and radiotherapy dosimetry, (2) to introduce cavity theories that are used in modern radiation dosimetry, (3) to summarize AAPM recommendations on reference/relative dosimetry for kV x-rays and high-energy photon and electron beams based TG 61 and TG 51, and (4) to describe dosimetry systems and methods for absorbed dose measurement.

Conflict of Interest: no

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