Dosimetry Fundamentals

Chapter 11

F.A. Attix, Introduction to Radiological Physics and Radiation Dosimetry

Outline

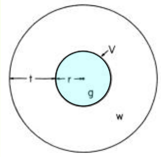
- Introduction
- Dosimeter model
- Interpretation of dosimeter measurements
  - – Photons and neutrons
  - – Charged particles
- General characteristics of dosimeters
- Summary

Introduction

- Radiation dosimetry deals with the *determination* (i.e., by measurement or calculation) of the absorbed dose or dose rate resulting from the interaction of ionizing radiation with matter
- Other radiologically relevant quantities are exposure, kerma, fluence, dose equivalent, energy imparted, etc. can be determined
- Measuring one quantity (usually the absorbed dose) another one can be derived through calculations based on the defined relationships

Dosimeter

- A *dosimeter* can be generally defined as any device that is capable of providing a reading R that is a measure of the absorbed dose D_g deposited in its *sensitive volume V* by ionizing radiation
- If the dose is not homogeneous throughout the sensitive volume, then R is a measure of mean value $\overline{D}_g$

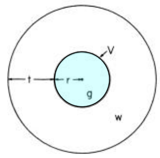


Dosimeter

- Ordinarily one is not interested in measuring the absorbed dose in a dosimeter’s sensitive volume itself, but rather as a means of determining the dose (or a related quantity) for another medium in which direct measurements are not feasible
- Interpretation of a dosimeter reading is the central problem in dosimetry, usually exceeding in difficulty the actual measurement

Simple dosimeter model

- A dosimeter can generally be considered as consisting of a sensitive volume V filled with a medium g, surrounded by a wall (or envelope, container, etc.) of another medium w having a thickness $t \geq 0$
- A simple dosimeter can be treated in terms of cavity theory, the sensitive volume being identified as the “cavity”, which may contain a gaseous, liquid, or solid medium g



Simple dosimeter model

- The *dosimeter wall* can serve a number of functions simultaneously:
  - being a source of secondary charged particles that contribute to the dose in *V*, and provide CPE or TCPE in some cases
  - shielding *V* from charged particles that originate outside the wall
  - protecting *V* from “hostile” influences such as mechanical damage, dirt, humidity, light, electrostatic or RF fields, etc., that may alter the reading
  - serving as a container for *g* that is a gas, liquid, or powder
  - containing radiation filters to modify the energy dependency of the dosimeter

Interpretation of dosimeter measurements: photons and neutrons

- Under CPE condition

$$D \overset{\text{CPE}}{=} K_c = \Psi\left(\mu_{\text{en}}/\rho\right)$$

- Consider a dosimeter with a wall of medium *w*, thick enough to exclude all charged particles generated elsewhere, and at least as thick as the maximum range of secondary charged particles generated in it by the photon or neutron field
- If the wall is uniformly irradiated, CPE exists in the wall near the cavity, therefore knowing D_w can calculate energy fluence Ψ of the primary field

Interpretation of dosimeter measurements: photons and neutrons

- The dosimeter reading provides us with a measure of the dose D_g in the dosimeter’s sensitive volume
- If the latter is small enough to satisfy the B-G conditions, we can find D_w from D_g
- The dose D_x in any other medium *x* replacing the dosimeter and given an identical irradiation under CPE conditions can be obtained from

$$D_x \overset{CPE}{=} D_w \frac{\left(\bar{\mu}_{en}/\rho\right)_x}{\left(\bar{\mu}_{en}/\rho\right)_w} \quad \text{for photons}$$

Interpretation of dosimeter measurements: photons and neutrons

- For neutrons the CPE condition results in

$$D \overset{\text{CPE}}{=} K = \Phi F_n$$

F_n is kerma-factor, Φ is neutron fluence

- Therefore the dose D_x in the medium of interest *x*

$$D_x \overset{\text{CPE}}{=} D_w \frac{\left(\bar{F}_n\right)_x}{\left(\bar{F}_n\right)_w} \quad \text{for neutrons}$$

Interpretation of dosimeter measurements: photons and neutrons

- For higher-energy radiation ($h\nu \geq 1$ MeV or $T_n \geq$ 10 MeV), CPE fails but TCPE takes its place in dosimeters with walls of sufficient thickness
- For photons TCPE condition provides relationship

$$D \overset{\text{TCPE}}{=} K_c\left(1+\mu'\bar{x}\right) \equiv K_c\beta = \Psi\left(\mu_{\text{en}}/\rho\right)\beta$$

- For neutrons

$$D \overset{\text{TCPE}}{=} K\left(1+\mu'\bar{x}\right) \equiv K\beta = \Phi F_n \beta$$

- Relating D_w to Ψ or Φ then requires evaluation of $\beta = D/K_c$ for each case

Interpretation of dosimeter measurements: photons and neutrons

- The exposure *X* (C/kg) for photons can in turn be derived from the absorbed dose D_{air} (for x = air) through this relation:

$$X \overset{\text{CPE}}{=} D_{\text{air}}\left(\frac{e}{\bar{W}}\right)_{\text{air}} = \frac{D_{\text{air}}}{33.97}$$

- This relationship can be extended for higher energies where TCPE exists, dividing D_{air} by β

Interpretation of dosimeter measurements: photons and neutrons

- The value of β is generally not much greater than unity for radiation energies up to a few tens of MeV, and it is not strongly dependent on atomic number
- Thus for media *w* and *x* not differing very greatly in *Z*, the equations for D_x are still approximately valid
- If the dosimeter has too large a sensitive volume for the application of B-G theory, Burlin theory can be used to calculate the equilibrium dose D_w from $\overline{D}_g$
  - requires sensitive-volume size *d* parameter

Advantages of media matching

- Matching parameters:
  - Atomic compositions
  - The density state (gaseous vs. condensed), which influences the collision-stopping-power ratios for electrons by the polarization effect
- Advantages:
  - Influence of cavity theory is minimized
  - No need to know the radiation energy spectrum

Advantages of media matching

- *w*=*g*: if the wall and sensitive-volume media of the dosimeter are identical with respect to composition and density, then $D_w = D_g$ for all homogeneous irradiations
- *w*=*g*=*x*: the dosimeter would be truly representative of that medium with respect to radiation interactions, and $D_x = D_w = D_g$
- Unfortunately, dosimeters are only available in a finite variety, therefore have to rely on cavity theory

Media matching in photon dosimeters (w=g)

- The Burlin cavity relation

$$\frac{\overline{D}_g}{D_w} = d \cdot {}_m\overline{S}_w^{\,g} + (1-d)\left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_w^g$$

- If *w* and *g* are matched, the doses $D_w = D_g$ and

$${}_m\overline{S}_w^{\,g} = \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_w^g = 1$$

- This relationship is hard to satisfy, especially for *w* and *g* of different atomic compositions

Media matching in photon dosimeters (w=g)

- A more flexible and practical relationship

$${}_m\overline{S}_w^{\,g} = \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_w^g = n$$

- The Burling relation then becomes independent of d since $\overline{D}_g / D_w = n$
- It is relevant, for example, if photons interact only by the Compton effect in *g* and *w*: μ_{en}/ρ ~the mass collision scattering power of the secondary electrons ~ to the number of electrons per gram, $N_A Z/A$; $n \approx (Z/A)_g/(Z/A)_w$

Matching the dosimeter to the medium of interest when w≠g

- If the wall medium *w*≠*g*, matching to medium *x* depends on the dosimeter volume size
- If the sensitive volume is small (*d* = 1 in Burlin's cavity theory), then the wall should be matched to medium *x*, to minimize the need for spectral information
- Dose in *x* can be obtained from

$$\frac{\overline{D}_g}{D_x} = \frac{\overline{D}_g}{D_w} \cdot \frac{D_w}{D_x} = {}_m\overline{S}_w^{\,g} \left(\frac{\overline{\mu}_{\mathrm{en}}}{\rho}\right)_x^w$$

Matching the dosimeter to the medium of interest when w≠g

- If the sensitive volume is large ($d = 0$ in Burlin’s cavity theory), the wall influence on the dose in the medium g is entirely lost
- Medium x should be matched to g and dose in x can be obtained from

$$\frac{\bar{D}_g}{D_x} = \frac{\bar{D}_g}{D_w} \cdot \frac{D_w}{D_x} = \left(\frac{\bar{\mu}_{\text{en}}}{\rho}\right)_w^g \left(\frac{\bar{\mu}_{\text{en}}}{\rho}\right)_x^w = \left(\frac{\bar{\mu}_{\text{en}}}{\rho}\right)_x^g$$

- For a general case of intermediate size cavity (0<d<1) full Burlin equation can be used to obtain D_w from D_g

Correcting for attenuation of radiation

- The problem arises from the difference in attenuation by media x (for example, water), w (thickness t) and g (radius r)
- The photon energy fluence reaching the center of a dosimeter

$$\Psi_{dos} \cong \Psi_0 \left[1 - \left(\frac{\mu_{en}}{\rho}\right)_w \rho_w t - \left(\frac{\mu_{en}}{\rho}\right)_g \rho_g r\right]$$

- On the other hand energy fluence reaching the water sphere replacing the dosimeter

$$\Psi_{wat} \cong \Psi_0 \left[1 - \left(\frac{\mu_{en}}{\rho}\right)_{wat} \rho_{wat} (t + r)\right]$$

- The dosimeter reading should be multiplied by $\Psi_{\text{wat}}/\Psi_{\text{dos}}$ to correct for the difference of attenuation in determining the dose to water at the dosimeter midpoint

Importance of dosimeter wall thickness

- Dosimeter wall thickness requirement depends on the goal of a measurement: to obtain a quantity that depends on
  a) the characteristics of the local photon or neutron field, the dosimeter should have a wall at least as *thick* as the maximum range of the charged particles present, to provide CPE or TCPE
  b) the characteristics of the local secondary charged-particle field then the dosimeter wall and sensitive volume should both be *thin* enough not to interfere with the passage of incident charged particles

Interpretation of dosimeter measurements: charged particles

- The absorbed dose at a point in a medium x is the product of the charged-particle fluence (*not* the energy fluence) and the mass collision stopping power, assuming that CPE exists for δ-rays

$$D_x = \int_0^{T_{\max}} \Phi(T) \left(\frac{dT}{\rho dx}\right)_{c,x} dT$$

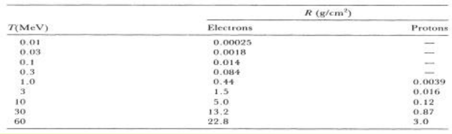
- The integration is over all energies in the primary (i.e., non-δ-ray) charged-particle spectrum Φ(T)

Interpretation of dosimeter measurements: charged particles

- Charged particle dosimeter needs a sensitive volume small (or thin) enough to satisfy the B-G conditions (nonperturbation of the charged-particle field), and all dose to be deposited only by crossers
- The dosimeter wall should be thick enough to serve any essential functions (e.g., containment)
- Thin flat pillbox- or coin-shaped dosimeters, oriented perpendicularly to the particle-beam direction, are used to satisfy these requirements

Interpretation of dosimeter measurements: charged particles

Approximate CSDA ranges of electrons and protons in water



	R (g/cm^2)	
T(MeV)	Electrons	Protons
0.01	0.00025	—
0.03	0.0018	—
0.1	0.014	—
0.3	0.084	—
1.0	0.44	0.0039
3	1.5	0.016
10	5.0	0.12
30	13.2	0.87
60	22.8	3.0

- As a rule of thumb: neither the wall thickness nor that of the sensitive volume should exceed ~1% of the range of the incident charged particles
- Ranges in other low-Z media are comparable

Interpretation of dosimeter measurements: charged particles

- One of the functions of the dosimeter wall is to provide δ-ray CPE for the sensitive volume
- This will occur if: 1) the wall matches the sensitive volume with respect to atomic number and density state, 2) is at least as thick as the δ-ray range, and 3) is uniformly irradiated throughout by the primary charged particles
- The importance of the wall as a δ-ray generator is greatest for measurements of the dose in free space
- For measurements where dosimeter is immersed in a medium:
  - Wall thickness is not important if the medium, the wall, and the sensitive volume are all similar in composition
  - If they differ significantly electron scattering affects the result the most

Interpretation of dosimeter measurements: charged particles

- There is no general and physically realistic cavity theory for relating the dose in a dosimeter to that in the medium at the point of measurement in an electron beam
- The problem appears to be with electron scattering, resulting in the measured dose dependence on the shape and orientation of the cavity
- A successful theory must account for it as a first-order effect

General characteristics of dosimeters

- Absoluteness
- Precision and accuracy
- Dose range
- Dose rate range
- Stability
- Energy dependence
- Miscellany (configuration, relevant calibration, reusability, etc.)

Absoluteness

- An *absolute dosimeter* can be assembled and used to measure the absorbed dose deposited in its own sensitive volume without requiring calibration in a known field of radiation
- It may need some calibration not involving radiation (e.g, electrical-heating for a calorimetric dosimeter)
- Calibration, however, offers certain advantages:
  - It can be stated in terms of some quantity of interest such as tissue dose (as opposed to dose in *g*) or exposure
  - It can also provide traceability to a standardization laboratory thus minimizing errors that may go undetected

Absoluteness

- Three types of dosimeters are generally regarded as being capable of absoluteness:
  - Calorimetric dosimeters
  - Ionization chambers
  - Fricke ferrous sulfate dosimeters
- The calorimetric dosimeter has the fundamental advantage of directly measuring the heat to which the absorbed dose degrades, without dependence on any coefficient of conversion such as to ionization or to chemical yield
- The absoluteness of a dosimeter is independent of its precision or its accuracy

Precision and accuracy

- The concept of the *precision* or reproducibility of dosimeter measurements has to do with random errors due to fluctuations in instrumental characteristics, ambient conditions, and so on, and the stochastic nature of radiation fields
- Precision can be estimated from the data obtained in repeated measurements, and is usually stated in terms of the standard deviation
- High precision is associated with a small standard deviation; a high-precision instrument is *capable* of excellent measurement reproducibility if properly used

Precision and accuracy

- The *accuracy* of dosimeter measurements expresses the proximity of their expectation value to the true value of the quantity being measured
- It is impossible to evaluate the accuracy of data from the data itself, as is done to assess their precision
- Accuracy is a measure of the collective effect of the errors that influence the measurements (proper calibration, exactly known volume, etc.), relevant to operation of the dosimeter as an absolute instrument
- In experiments that are limited to relative measurements, only the precision is important

Dose range: sensitivity

- To be useful, a dosimeter must have adequate *dose sensitivity* throughout the dose range to be measured
- A constant dose sensitivity throughout the range provides a linear response (dr/dD_g=const), that is desirable for ease of calibration and interpretation
- However, knowing the function $r(D_g)$, even nonlinear but single-valued, may be acceptable, though it requires that the calibration be carried out at multiple doses to provide a calibration curve

Dose range: lower limit

- The lower limit of the useful dose range may be imposed by the *instrumental background* or zero-dose reading r_0, observed when $D_g = 0$ (sometimes referred to as "spurious response")
- Examples of r_0 include charge readings due to ion-chamber insulator leakage, and thermo-luminescence dosimeter readings resulting from response of the reader to infrared light emission by the dosimeter heater
- The instrumental background should be subtracted from any dosimeter reading

Dose range: lower limit

- The lower limit of the practical dose range of a dosimeter is usually estimated to be the dose necessary to double the instrumental background reading
- If σ' is the S.D. of the average of a group of radiation readings r, and σ'_0 is the S.D. of the average of the background readings r_0, then the S.D. of the net radiation reading $r - r_0$ is given by

$$\sigma'_{\text{net}} = \sqrt{(\sigma')^2 + (\sigma'_0)^2}$$

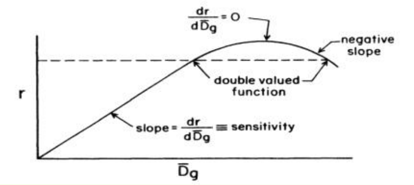
Dose range: lower limit

- If the background reading is negligibly small, then the lower dose limit is imposed by the capability of the dosimeter readout instrument to provide a readable value of r for the dose to be measured D_g
- Readable value r is typically considered to be $\geq$10% of full scale on analogue instruments, or contain more than three significant figures on digital readouts
- A more sensitive scale may be required

Dose range: upper limit

- The upper limit of the useful dose range of a dosimeter may be imposed simply by external instrumental limitations (reading off scale of an electrometer)
- Alternatively, an inherent limit may be imposed by the dosimeter itself due to:
  - a) Exhaustion of the supply of atoms, molecules, or solid-state entities ("traps") being acted upon by the radiation to produce the reading
  - b) Competing reactions by radiation products, for example in chemical dosimeters
  - c) Radiation damage to the dosimeter (e.g., discoloration of light-emitting dosimeters, damage to electrical insulators)

Dose range: upper limit



- Usually the upper limit of the dose range is manifested by a decrease in the dose sensitivity (dr/dD_g) to an unacceptable value
- It may be reduced to zero, or to a negative value, which causes the dose-response function to become double-valued

Dose-rate range: integrating dosimeters

- If a dosimeter is used for measuring the time-integrated dose (not the dose rate), then its reading should not depend on the dose rate
- Usually the low-dose-rate limitation is imposed by the lower dose limits of the dosimeter
- One case of a genuine low-dose-rate limitation is *reciprocity-law failure* in photographic film dosimeters
  - It occurs only with low-LET radiation (x rays or electrons)
  - It is due to the necessity for several ionizing events to occur in a single grain of silver bromide to make it developable

Dose-rate range: integrating dosimeters

- The upper limit of dose-rate independence usually occurs when charged-particle tracks are created close enough together in space and time to allow the ions, electron-hole pairs, or active chemical products such as free radicals to interact between tracks
- In an ion chamber this is called general or volume ionic recombination
- Similar back reactions also occur in solid or liquid dosimeters, resulting in a loss of contribution to the reading *r*

Dose-rate range: dose-rate meters

- The dose-rate-measuring dosimeters should provide readings proportional to the dose rate dD_g/dt, or at least to be a single-valued function of it
- The upper limit on the usable dose-rate range is usually imposed by saturation such as ionic recombination, etc.
- The counting of two or more events as one when they occur temporally too close together in pulse-counting dosimeters also may cause saturation
- The *response time constant* characterizes the capability of the dosimeter to resolve separate pulses and possibly measure the pulse shape in a pulsed radiation field

Stability

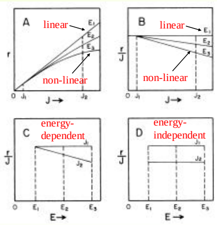
- The characteristics of a dosimeter should be stable with time until it is used
- That includes “shelf life” and time spent *in situ* until irradiated (e.g., worn by personnel if a health-physics monitoring dosimeter)
- Effects of temperature, atmospheric oxygen or humidity, light, and so on can cause a gradual change in the dose sensitivity or the instrumental background
- Photographic, chemical, or solid-state dosimeters are generally more susceptible to these influences than ion chambers or counters

Stability

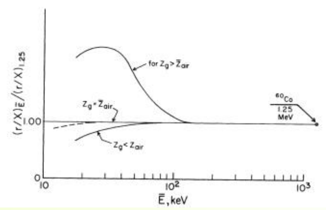
- After irradiation the latent reading in some types of integrating dosimeters (e.g., photographic, chemical, solid-state) may be unstable, suffering “fading” losses during the time interval between irradiation and readout
- Harsh ambient conditions may aggravate this effect
- If time-dependent fading losses are unavoidable, it is advantageous to make them as reproducible as possible through standardization of laboratory technique so that a fading correction can be applied to the readings

Energy dependence

- The *energy dependence* of a dosimeter is the dependence of its reading r, per unit of the quantity it is supposed to measure, upon the quantum or kinetic energy of the radiation
- The reading r obtained from a dosimeter vs. some dosimetric quantity J (such as exposure, absorbed dose in water, etc.)
- A: The calibration curves obtained at the three different energies
- C: Plot r/J vs. energy to obtain the *energy-dependence curves;* for J_1 and J_2 they are different for $E > E_1$
- D: Energy-independent dosimeter: r vs. J is the same for all energies



Energy dependence in health physics



- Dependence of the dosimeter reading, per unit of x- or γ-ray exposure, on the quality of the beam, r/X vs. E
- ^{60}Co γ-rays are frequently used as the reference energy for normalization, producing energy-dependence curves for dosimeters made of materials >, =, and < than *air* in atomic number

Energy dependence in health physics

- The shape of the curves can be estimated by:

$$\frac{\left(\dfrac{r}{X}\right)_{\bar{E}}}{\left(\dfrac{r}{X}\right)_{1.25}} \cong \frac{\left[\dfrac{(\mu_{\text{en}}/\rho)_g}{(\mu_{\text{en}}/\rho)_{\text{air}}}\right]_{\bar{E}}}{\left[\dfrac{(\mu_{\text{en}}/\rho)_g}{(\mu_{\text{en}}/\rho)_{\text{air}}}\right]_{1.25}}$$

where g refers to the material in the dosimeter's sensitive volume

- This equation is based on the assumptions that:
  1. The dosimeter's sensitive volume is in charged-particle equilibrium, and the wall medium $w = g$
  2. Attenuation is negligible in the dosimeter, both for incident photons and fluorescence photons generated in the dosimeter
  3. A given absorbed dose to the sensitive volume produces the same reading, irrespective of photon energy (i.e., the dosimeter is LET-independent)

Energy dependence in radiation therapy: absorbed dose

- Dependence of the dosimeter reading per unit of absorbed dose in water on the photon or electron-beam energy
- "Absorbed dose" always refers to water (or muscle tissue) unless otherwise specified
- In the megavolt region the differences between water and tissue are small (~1%)

Energy dependence in radiation therapy: absorbed dose

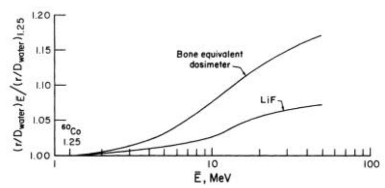
- For x rays the equation by which a homogeneous dosimeter's energy dependence can be estimated is

$$\frac{(r/D_{\text{water}})_{\bar{E}}}{(r/D_{\text{water}})_{1.25}} \cong \frac{\left[(\mu_{\text{en}}/\rho)_g/(\mu_{\text{en}}/\rho)_{\text{water}}\right]_{\bar{E}}}{\left[(\mu_{\text{en}}/\rho)_g/(\mu_{\text{en}}/\rho)_{\text{water}}\right]_{1.25}}$$

which depends on water as a reference material and ^{60}Co γ rays for normalization

- This equation can be used over the energy range from 1.25 to 50 MeV for LiF and bone-equivalent dosimeters

Energy dependence in radiation therapy : absorbed dose



- X-ray energy dependence estimated for a LiF and a bone-equivalent dosimeter, in terms of response per unit absorbed dose in water, normalized to ^{60}Co γ rays
- The rise at higher energies results from increase in pair production

Energy dependence in radiation therapy : absorbed dose

- Because of the large secondary-electron ranges at MeV energies, this equation is only satisfied to the extent that TCPE is present, $g = w$, and parameter β is the same in water as in the dosimeter
- This requires wall thickness that would produce considerable x-ray attenuation, and just be impractical for the size of the resulting dosimeter
- In radiotherapy dosimetry these problems are usually avoided by doing the measurements in a phantom, letting it comprise most of the dosimeter's wall thickness

Energy dependence in radiation therapy: absorbed dose

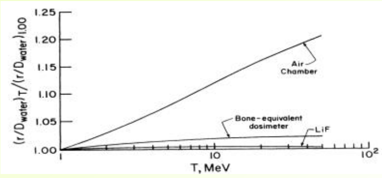
- For electron beams of kinetic energy T (MeV), the corresponding equation for estimating energy dependence in terms of the dose to water, normalized to $T = 1$ MeV, is

$$\frac{\left(\dfrac{r}{D_{\text{water}}}\right)_T}{\left(\dfrac{r}{D_{\text{water}}}\right)_{1\text{ MeV}}} \cong \frac{\left[\dfrac{(dT/\rho dx)_{c,g}}{(dT/\rho dx)_{c,\text{water}}}\right]_T}{\left[\dfrac{(dT/\rho dx)_{c,g}}{(dT/\rho dx)_{c,\text{water}}}\right]_{1\text{ MeV}}}$$

Energy dependence in radiation therapy: absorbed dose

- This approximation assumes that:
  1. CPE exists for δ-rays entering and leaving the sensitive volume
  2. The incident electrons lose only a very small fraction of their energy in traversing the dosimeter
  3. Electron scattering is the same in g as in water
  4. The reading per unit dose to the dosimeter's sensitive volume remains energy-independent ("LET-independent")
- Items 1 and 3 are suspect, while 2 and 4 are easily satisfied in the energy region above 1 MeV

Energy dependence in radiation therapy: absorbed dose



- Electron-energy dependence estimated for LiF, a bone-equivalent dosimeter, and an air-filled ion chamber, in terms of response per unit absorbed dose in water, normalized to $T = 1$ MeV
- Neither LiF nor a bone-equivalent dosimeter shows much dependence since collision stopping-power ratios are insensitive to electron energy unless the polarization effect is involved

Energy dependence

- Dependence of the dosimeter reading per unit of absorbed dose to the material in the sensitive volume itself, on the radiation energy or beam quality
- The most fundamental as it reflects the dosimeter's energy efficiency, i.e., the ability of the dosimeter to give the same reading for the same amount of absorbed energy in its own sensitive volume, regardless of radiation type or quality
- It is often called "LET dependence" because it usually manifests itself as a change in the reading per unit dose as a function of charged-particle track density, due to ionic recombination or other second-order effects that depend on the proximity of radiation products to the dosimeter

Miscellany

- The *configuration* of a dosimeter sometimes is crucial to its use; for example, small size of a dosimeter is of primary importance in its application *in vivo* in patients or test animals
- A dosimeter needs a *relevant calibration* that is appropriate to the radiation type and quality, as well as to the quantity to be measured
- The *reusability* of a dosimeter has several important implications: reusable TLDs can be individually calibrated; single-use dosimeters such as film badges cannot

Summary

- General dosimeter model
- Interpretation of dosimeter measurements
  - Photons and neutrons

$$D_x \overset{\text{CPE}}{=} D_w \frac{(\bar{\mu}_{\text{en}}/\rho)_x}{(\bar{\mu}_{\text{en}}/\rho)_w} \quad \text{for photons}$$

  - Charged particles

$$D_x = \int_0^{T_{\max}} \Phi(T) \left(\frac{dT}{\rho dx}\right)_{c,x} dT$$

- General characteristics of dosimeters: absoluteness, precision and accuracy, dose range, dose rate range, stability, energy dependence, and others