Chapter 5: Radiation Dosimetry

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Units for Absorbed Dose

- **Radiation damage** depends on the energy absorption from the radiation and is **approximately proportional to the concentration of absorbed energy in tissue**.
- The basic unit of radiation dose is expressed in terms of absorbed energy per unit mass of tissue, which is called **Gary (Gy)**

$$1Gy = 1J/Kg = 100rad$$

$$\text{where Rad stands for Radiation Absorbed Dose, which is a non-SI unit.}$$

- The Gary is universally applicable to all types of ionizing radiation dosimetry – irradiation due to external field of gamma rays, neutrons or charged particles as well as that due to internally deposited radioisotopes.

The SI Unit for Exposure

- For external radiation of any given energy flux, the absorbed dose to any point within an organism depends on the type and energy of radiation, the depth within the organism of the point at which the absorbed dose is required and the elemental composition of the absorbing medium at that point.
- The x-ray fields to which an organism may be exposed is normally specified in **exposure unit**.

$$1\ X\ unit = 1C/Kg\ \text{air}$$

$$1\ \text{X unit} = 1\,\frac{\text{C}}{\text{kg air}} \times \frac{1\ \text{ion}}{1.6\times10^{-19}\ \text{C}} \times 34\,\frac{\text{eV}}{\text{ion}} \times 1.6\times10^{-19}\,\frac{\text{J}}{\text{eV}} \times 1\,\frac{\text{Gy}}{\text{J/kg}}$$
$$= 34\ \text{Gy (in air)}.$$

- Alternatively, exposure is also measured with the unit Roentgen (R),

$$1\ \text{R} = 2.58\times10^{-4}\ \text{C}\cdot\text{kg}^{-1}$$

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- Units of exposure and dose
- Methods for measuring absorbed dose.
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  2. **Exposure-dose relationship**
  3. Direct measurement of absorbed dose: **Bragg-Gray Principle**
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- Beta radiation
  1. Dose from **contaminated surface**
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  3. **Submersion dose**
- Internally deposited radioisotopes
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  2. **Effective half-life**
  3. **Total dose commitment**
  4. Evaluate the **internal dose from gamma ray emitters**
  5. **MIRD method** – partial energy absorption of gamma ray energy in tissues
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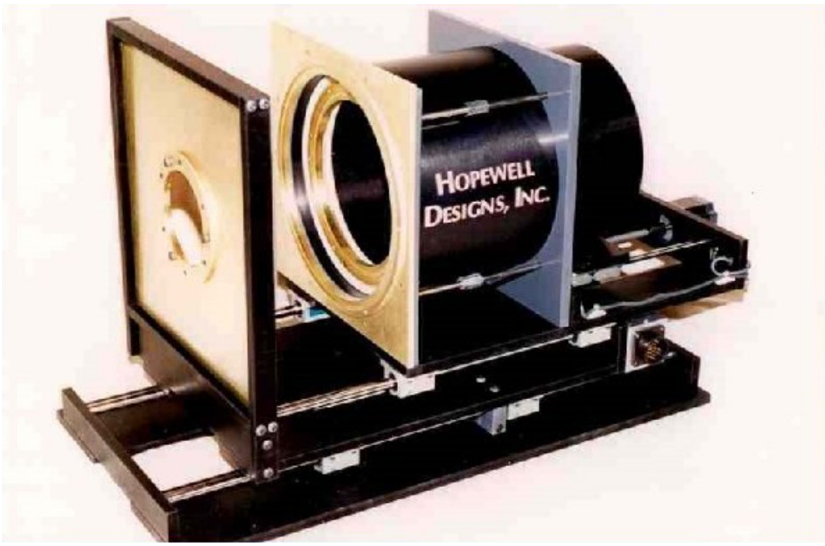
Exposure Measurement: The Free Air Chamber



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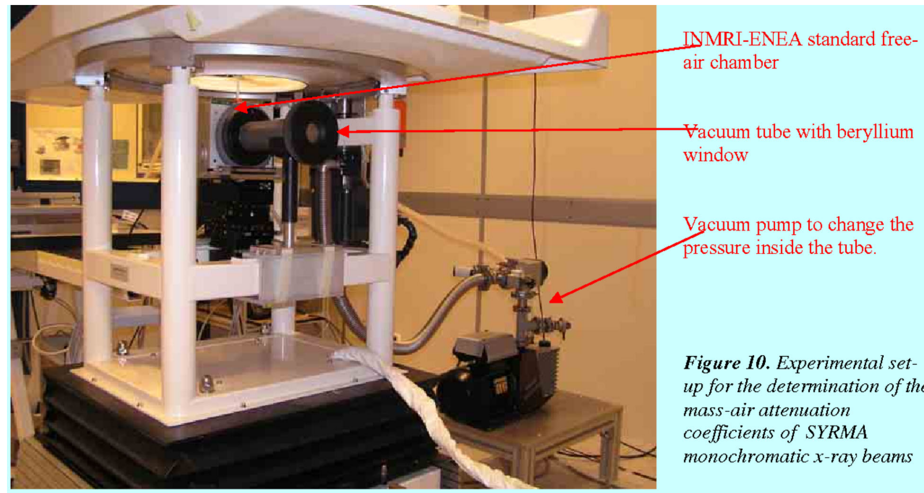


Figure 10. *Experimental set-up for the determination of the mass-air attenuation coefficients of SYRMA monochromatic x-ray beams*

ABSOLUTE AIR-KERMA MEASUREMENT IN A SYNCHROTRON RADIATION BEAM BY IONIZATION FREE-AIR CHAMBER

R. Laitano, M. Pimpinella, +7 authors A. Vascotto • Published 2007

A dosimetric procedure to assure the traceability to the air-kerma standard of the measurements performed in synchrotron radiation beams, was implemented at the “Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti” of ENEA (INMRI-ENEA). To this purpose, absolute air-kerma measurements by the ENEA standard free-air chamber for low energy x-rays have been performed at the SYRMEP (SYnchrotron Radiation for Medical Physics) beamline of the ELETTRA light source in Trieste (Italy) where a... CONTINUE READING

Exposure Measurement: The Free Air Chamber

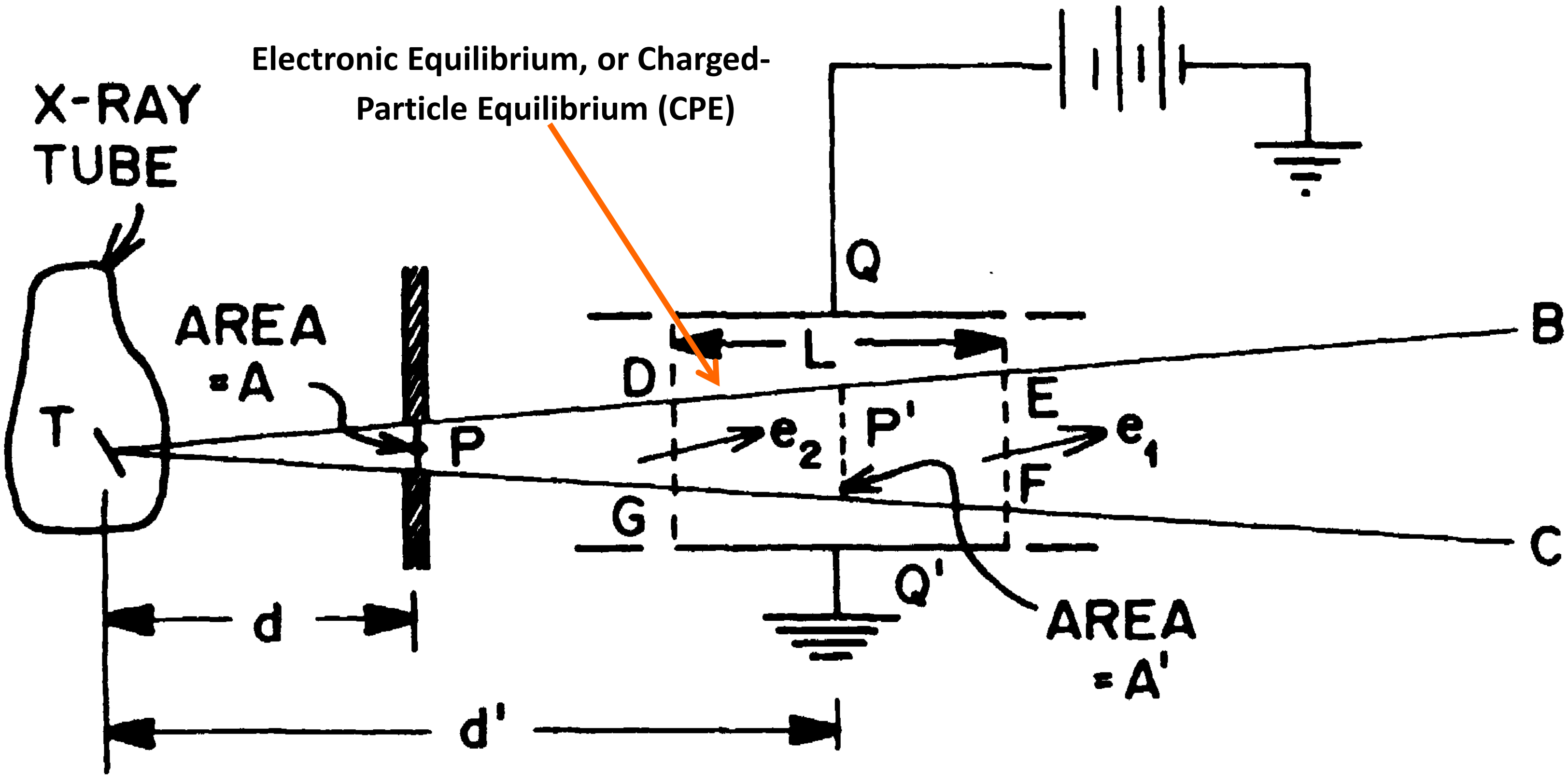


Fig. 12.1 Schematic diagram of the "free-air" or "standard" ionization chamber.

Turner, pp. 365.

Charged-Particle Equilibrium (CPE)

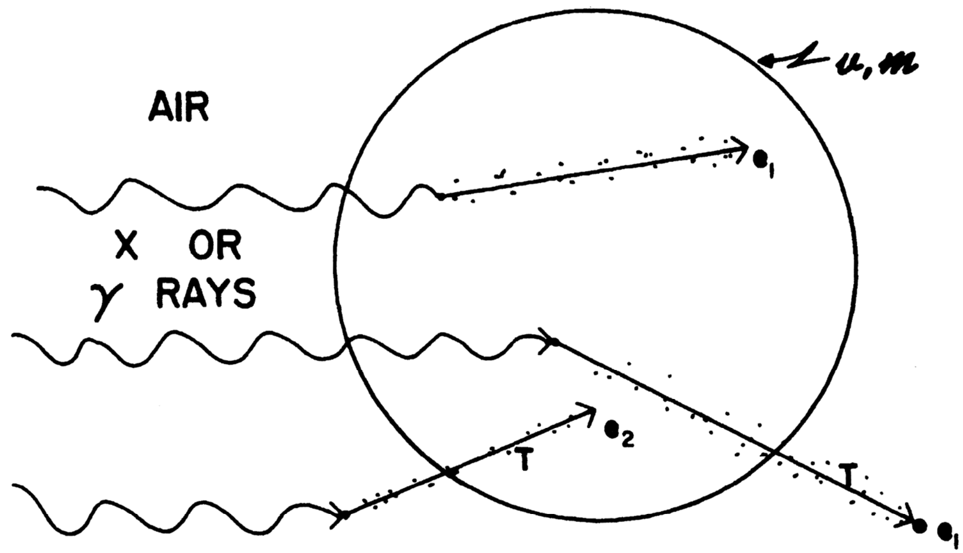


FIGURE 4.5. The role of CPE in the measurement of exposure X. The average exposure in the finite air volume v equals the total charge of either sign released in air by all electrons (e_1) that originate in v, divided by the air mass m in v. If CPE exists, each electron carrying an energy (say, T) out of v is compensated by another electron (e_2) carrying the same energy in. Thus the same ionization occurs in v as if all electrons e_1 remained there. The measurement of that charge divided by m is thus equivalent to a measurement of the average exposure in v. Radiative losses are assumed to escape from v, and any ionization they produce is not to be included in X.

From <<Introduction to Radiological Physics and Radiation Dosimetry>>

Exposure Measurement: The Free Air Chamber

The exposure in the volume $DEFG$ in roentgens would be determined directly if the total ionization produced only by those ions that originate from X-ray interactions in the truncated conical volume $DEFG$ could be collected and the resulting charge divided by the mass of air in $DEFG$. This mass is given by $M = \rho A'L$, where ρ is the density of air, A' is the cross-sectional area of the truncated cone at its midpoint P', and L, the thickness of the cone, is equal to the length of the collecting plates Q and Q'. Unfortunately, the plates collect all of the ions between them, not the particular set that is specified in the definition of the roentgen. Some electrons produced by X-ray interactions in $DEFG$ escape this volume and produce ions that are not collected by the plates Q, Q'. Also, some ions from electrons originally produced outside $DEFG$ are collected. Thus, only part of the ionization of an electron such as e_1 in Fig. 12.1 is collected, while ionization from an "outside" electron, such as e_2, is collected. When the distance from P to DG is sufficiently large (e.g., $\sim$ 10 cm for 300-keV X rays) electronic equilibrium will be realized; that is, there will be almost exact compensation between ionization lost from the volume $DEFG$ by electrons, such as e_1, that escape and ionization gained from electrons, such as e_2, that enter. The distance from P to DG, however, should not be so large as to attenuate the beam significantly between P and P'. Under these conditions, when a charge q is collected, the exposure at P' is given by

$$E_{P'} = \frac{q}{\rho A'L}. \qquad (12.6)$$

Exposure Measurement: The Free Air Chamber

in order to attain electronic equilibrium. For highly filtered 250-kV X-rays, 9 cm of air is required; for 500-kV X-rays, the air thickness required for electronic equilibrium in the sensitive volume increases to 40 cm. Under conditions of electronic equilibrium and assuming negligible attenuation of the X-ray beam by the air in length 1, the ions collected from the sensitive volume result from primary photon interactions at the beam entrance port; the measured exposure, consequently, is at that point and not in the sensitive volume. Free air chambers are in use that measure the quantity of X-rays whose quantum energies reach as high as 500 keV. Higher-energy radiation necessitates free air chambers of much greater size. The technical problems arising from the use of such large chambers make it impractical to use the free air ionization chamber as a primary measuring device for quantum energies in excess of 500 keV.

Exposure Measurement: The Free Air Chamber

Example

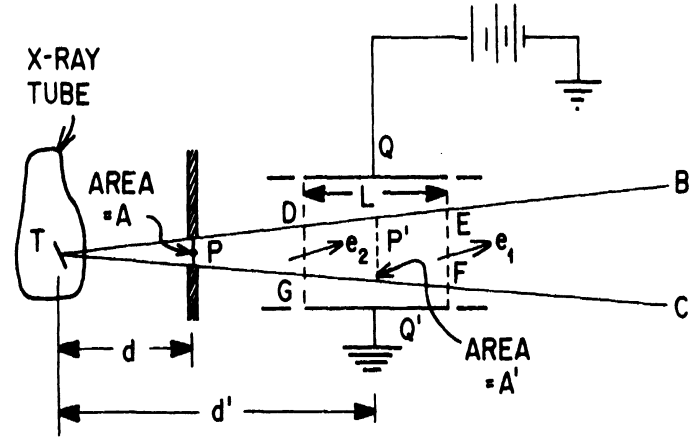
The entrance port of a free-air ionization chamber has a diameter of 0.25 cm and the length of the collecting plates is 6 cm. Exposure to an X-ray beam produces a steady current of 2.6×10^{-10} A for 30 s. The temperature is 26°C and the pressure is 750 torr. Calculate the exposure rate and the exposure. ?

Solution

We can apply Eq. (12.7) to exposure rates as well as to exposure. The rate of charge collection is $\dot{q} = 2.6 \times 10^{-10}\ \mathrm{A} = 2.6 \times 10^{-10}\ \mathrm{C\,s^{-1}}$. The density of the air under the stated conditions is $\rho = (0.00129)(273/299)(750/760) = 1.16 \times 10^{-3}\ \mathrm{g\,cm^{-3}}$. The entrance-port area is $A = \pi(0.125)^2 = 4.91 \times 10^{-2}\ \mathrm{cm^2}$ and $L = 6$ cm. Equation (12.7) implies, for the exposure rate,

$$\dot{E}_P = \frac{\dot{q}}{\rho A L} = \frac{2.6 \times 10^{-10}\ \mathrm{C\,s^{-1}}}{1.16 \times 10^{-3} \times 4.91 \times 10^{-2} \times 6\ \mathrm{g}} \times \frac{1\ \mathrm{R}}{2.58 \times 10^{-7}\ \mathrm{C\,g^{-1}}} = 2.95\ \mathrm{R\,s^{-1}}.$$

The total exposure is 88.5 R.



Exposure Measurement: The Air Wall Chamber

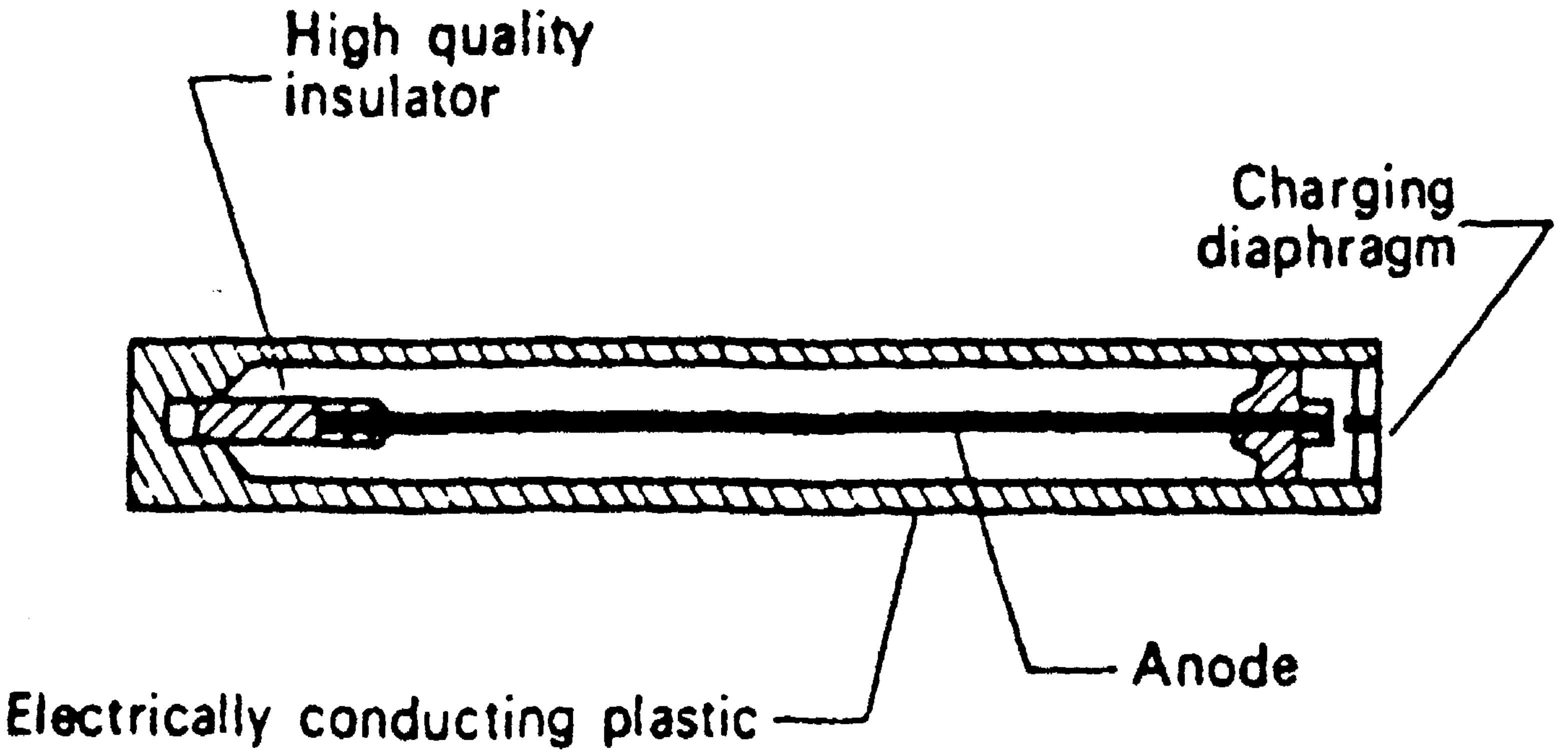


FIGURE 6.2. Non-self-reading condenser-type pocket ionization chamber.

Exposure Measurement: The Air Wall Chamber

Example 6.3

Chamber volume = 2 cm^3.

Chamber filled with air at STP.

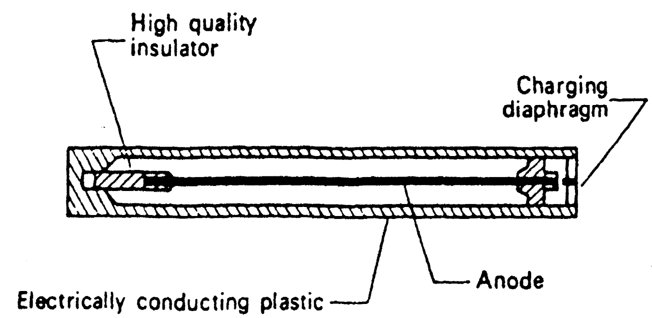
Electrical capacity = 5 μμF.

Voltage across chamber before exposure to radiation = 180 V.

Voltage across chamber after exposure to radiation = 160 V.

Exposure time = $\frac{1}{2}$ h.

Calculate the radiation exposure and the exposure rate.



Solution

The exposure is calculated as follows:

$$C \times \Delta V = \Delta Q \qquad (6.8)$$

$$5 \times 10^{-12} \text{ farads} \times (180 - 160) \text{ volts} = 1 \times 10^{-10} \text{ coulombs.}$$

Since one exposure unit is equal to 1 C/kg, the exposure measured by this chamber is

$$\frac{1 \times 10^{-10}\ \text{C}}{2\ \text{cm}^3 \times 1.293 \times 10^{-6}\ \text{kg/cm}^3} = 3.867 \times 10^{-5}\ \text{C/kg},$$

which corresponds to

$$3.867 \times 10^{-5}\ \text{C/kg} \times 3881 \frac{\text{R}}{\text{C/kg}} = 0.150\ \text{R},$$

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Does-Exposure Relationship

- Air wall chamber measures exposure in air, which should in some instances, be converted to the energy absorption in tissue.

- Since energy absorption is approximately proportional to the electron density of the absorber in the energy region where exposure units are valid, the tissue does is NOT necessarily equal to the air dose for any given exposure.

Exposure Measurement: The Free Air Chamber

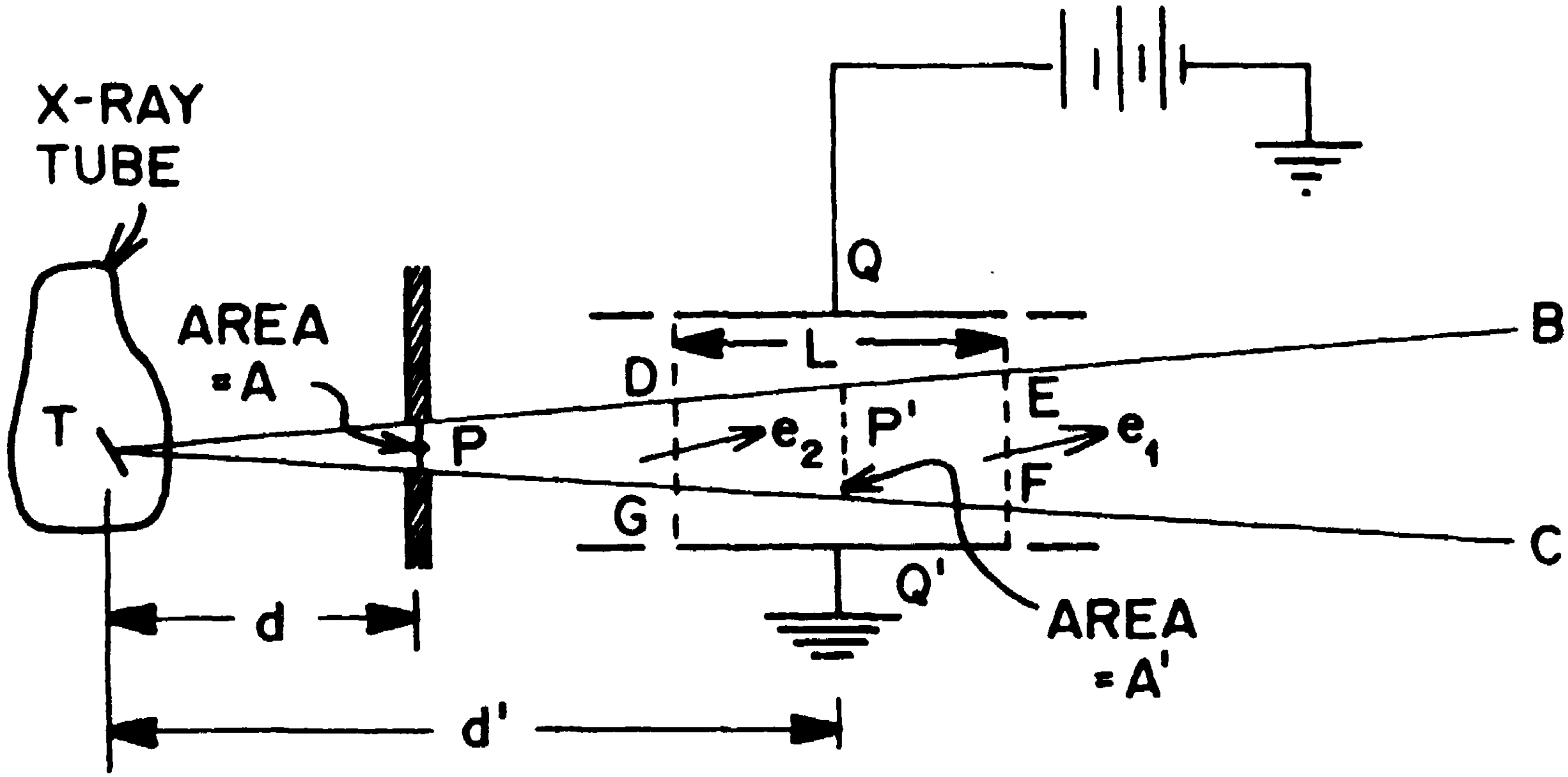


Fig. 12.1 Schematic diagram of the "free-air" or "standard" ionization chamber.

How do we convert the exposure measured with a free-air chamber to dose to tissue exposure to the same x-ray radiation field?

The SI Unit for Exposure

- For external radiation of any given energy flux, the absorbed dose to any point within an organism depends on the type and energy of radiation, the depth within the organism of the point at which the absorbed dose is required and the elemental composition of the absorbing medium at that point.
- The x-ray fields to which an organism may be exposed is normally specified in **exposure unit**.

$$1\ X\ unit = 1C / Kg\ \text{air}$$

$$1\ \text{X unit} \Leftrightarrow 1\,\frac{\text{C}}{\text{kg air}} \times \frac{1\ \text{ion}}{1.6 \times 10^{-19}\ \text{C}} \times 34\,\frac{\text{eV}}{\text{ion}} \times 1.6 \times 10^{-19}\,\frac{\text{J}}{\text{eV}} \times 1\,\frac{\text{Gy}}{\text{J/kg}}$$

$$1\ \text{X unit} \Leftrightarrow 34\ \text{Gy (in air)}.$$

- Alternatively, exposure is also measured with the unit Roentgen (R),

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

Does-Exposure Relationship

- Another example (Cember, p178)

Consider a gamma-ray beam of quantum energy 0.3 MeV. If the photon flux 1000 quanta/cm^2/s, and the air temperature is 20°C, what is the exposure rate at a point in this beam and what is the absorbed dose rate for soft tissue at this point?

The exposure rate in C/kg/s is given by

$$\dot{X} = \frac{\phi \text{ photons/cm}^2\text{-s} \times E \text{ MeV/photon} \times 1.6 \times 10^{-13} \text{ J/MeV} \times \mu_a \text{ cm}^{-1}}{\rho_a \text{ kg/cm}^3 \times 34 \dfrac{\text{J/kg}}{\text{C/kg}}}$$

where

μ_a is the linear energy absorption coefficient for air for the photon energy and ρ_a is the density of air.

Energy Transfer by a Gamma Ray Beam

Compton scattering

All Compton scattered gamma rays escaped

Multiple Compton scattering ignored

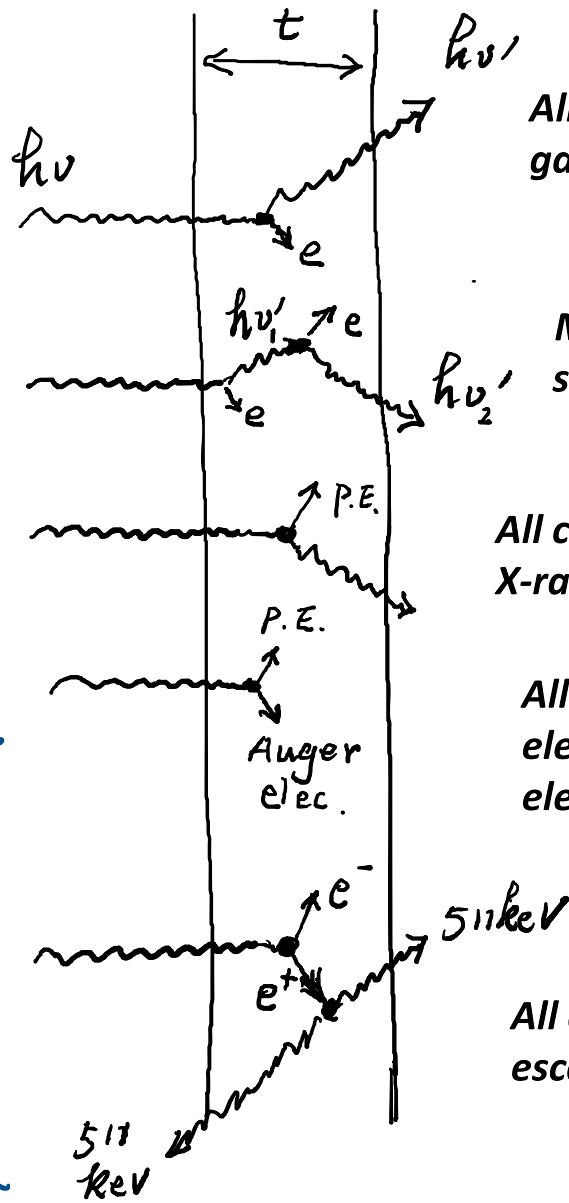
Photoelectric effect

All characteristic X-rays escaped

All photoelectrons, auger electrons and Compton recoil electrons are absorbed

Pair production

All annihilation gamma rays escaped



What is Energy Absorption Coefficients?

The total mass energy transfer coefficient is given by

$$\frac{\mu_{tr}}{\rho} = \frac{\tau}{\rho}\left(1 - \frac{\delta}{h\upsilon}\right) + \frac{\sigma}{\rho}\left(\frac{E_{avg}}{h\upsilon}\right) + \frac{\kappa}{\rho}\left(1 - \frac{2mc^2}{h\upsilon}\right)$$

Consider the fraction of energy that may be carried away by the subsequent bremsstrahlung photons, one can define the mass energy-absorption coefficient as

$$\frac{\mu_{en}}{\rho} = \frac{\mu_{tr}}{\rho}\left(1 - g\right)$$

where g is the average fraction of energy of the initial kinetic energy transferred to electrons that is subsequently emitted as bremsstrahlung photons.

Calculation of Energy Transfer and Energy Absorption

For simplicity, we consider an idealized case, in which

- **Photons are assumed to be monoenergetic and in broad parallel beam.**
- **Multiple Compton scattering of photons is negligible.**
- **Virtually all fluorescence and bremsstrahlung photons escape from the absorber.**
- **All secondary electrons (Auger electrons, photoelectrons and Compton electrons) generated are stopped in the slab.**

Under these conditions, the transmitted energy intensity (the amount of energy transmitted through a unit area within each second) can be given by

$$\dot{\Psi} = \dot{\Psi}_0 e^{-\mu_{en} x}$$

Calculation of Energy Transfer and Energy Absorption

Assuming $\mu_{en}x<<1$, which is consistent with the thin slab approximation and the energy fluence rate carried by the incident gamma ray beam is $\dot{\Psi}_0(\mathrm{J}\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1})$. Then the energy absorbed in the thin slab per second over a unit cross section area is given by

$$\Delta\dot{\Psi} = \dot{\Psi}_0 - \dot{\Psi} = \dot{\Psi}_0(1 - e^{-\mu_{en}x}) \approx \dot{\Psi}_0\mu_{en}x \ \ (J\cdot cm^{-2}\cdot s^{-1})$$

The rate of energy absorbed in the slab of area A (cm^2) and thickness x is

$$A\dot{\Psi}_0\mu_{en}x \ (J\cdot s^{-1})$$

Given the density of the material is ρ, the rate of energy absorption per unit mass (Dose Rate) in the slab is

$$\dot{D} = \frac{A(cm^2)\cdot\dot{\Psi}_0(J\cdot cm^{-2}\cdot s^{-1})\cdot\mu_{en}(cm^{-1})\cdot x\ (cm)}{\rho(g\cdot cm^{-3})\cdot A(cm^2)\cdot x(cm)},$$

$$\textit{Dose rate in the absorber:}\ \ \dot{\boldsymbol{D}}(J\cdot g^{-1}\cdot s^{-1}) = \dot{\boldsymbol{\Psi}}_{\boldsymbol{0}}(J\cdot cm^{-2}\cdot s^{-1})\frac{\boldsymbol{\mu}_{\boldsymbol{en}}(cm^{-1})}{\boldsymbol{\rho}(g/cm^3)}$$

Does-Exposure Relationship

- Another example (Cember, p178)

Consider a gamma-ray beam of quantum energy 0.3 MeV. If the photon flux 1000 quanta/cm^2/s, and the air temperature is 20°C, what is the exposure rate at a point in this beam and what is the absorbed dose rate for soft tissue at this point?

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where

μ_a is the linear energy absorption coefficient for air for the photon energy and ρ_a is the density of air.

Does-Exposure Relationship

The absorbed dose rate, in grays per second, is given by

$$\dot{D} = \frac{\frac{\phi \text{ photons/cm}^2}{\text{s}} \times E \text{ MeV/photon} \times 1.6 \times 10^{-13} \text{ J/MeV} \times \mu_m \text{ cm}^{-1}}{\rho_m \text{ kg/cm}^3 \times \frac{\text{J/kg}}{\text{Gy}}}$$

$$\dot{D} = \frac{\phi \cdot E \cdot \mu_m}{\rho_m}$$

$$\dot{X} = \frac{\phi \cdot E \cdot \mu_a}{\rho_a}$$

where

μ_m is the linear energy absorption coefficient of the medium and
ρ_m is the density of the medium.

Does-Exposure Relationship

- The relationship between exposure and dose is obtained from the ratio of the absorbed dose rate and the exposure rate,

$$\frac{\dot{D}}{\dot{X}} = \frac{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_m)/\rho_m}{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_a)/(\rho_a \times 34)}$$

$$\dot{D} = 34 \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \dot{X}\ \mathrm{Gy/s}.$$

- For an X-ray flux that could induce 1 X-unit of exposure in air, it could lead to the following amount of dose in a given tissue

$$\dot{D} = 34 \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a}$$

μ_{m} is the linear energy absorption coefficient of the medium and
ρ_{m} is the density of the medium.

μ_a is the linear energy absorption coefficient for air for the photon energy and
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Does-Exposure Relationship

- The relationship between exposure and dose is obtained from the ratio of the absorbed dose rate and the exposure rate,

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$$\dot{D} = 34 \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \dot{X}\ \mathrm{Gy/s}.$$

- For an X-ray flux that could induce 1 X unit of exposure in air, it could lead to

  and similarly

$$\text{rads} = \frac{87.7}{100} \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \text{roentgens}$$

μ_{m} is the linear energy absorption coefficient of the medium and
ρ_{m} is the density of the medium.
μ_a is the linear energy absorption coefficient for air for the photon energy and
ρ_a is the density of air.

Does-Exposure Relationship

An example:

in air

What is the radiation absorbed dose corresponding to an exposure of 25.8 μC/kg (100 mR) from 300-keV photons?

Solution

When the value for the energy absorption coefficient for muscle tissue for 0.3-MeV photons, $\mu_{\text{medium}} = 0.0317\ \text{cm}^2/\text{g}$ and $\mu_{\text{air}} = 0.0288\ \text{cm}^2/\text{g}$, from Table 5-4, are substituted into Eq. (6.12a), we have

$$\text{Dose} = 34\frac{\text{Gy}}{\text{C/kg}} \times \frac{0.0317\,\text{cm}^2/\text{g}}{0.0288\,\text{cm}^2/\text{g}} \times 25.8 \times 10^{-6}\,\frac{\text{C}}{\text{kg}} = 9.7 \times 10^{-4}\,\text{Gy}$$

$$\frac{\dot{D}}{\dot{X}} = \frac{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_m)/\rho_m}{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_a)/(\rho_a \times 34)}$$

$$\dot{D} = 34 \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \dot{X}\ \text{Gy/s}.$$

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$$= 34\ \text{Gy (in air)}.$$

→ what about in a different media?

- Alternatively, exposure is also measured with the unit Roentgen (R),

$$1\ \text{R} = 2.58\times10^{-4}\ \text{C}\cdot\text{kg}^{-1}$$

Does-Exposure Relationship

A few remarks:

- ☞ In the case of tissue, the ratio of dose to exposure remains approximately constant over the quantum energy range of about 0.1 to 10MeV. (Why?)
- ☞ At lower energy, material with greater atomic number absorbs much more energy.

$$\frac{\dot{D}}{\dot{X}} = \frac{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_m)/\rho_m}{(\phi \times E \times 1.6 \times 10^{-13} \times \mu_a)/(\rho_a \times 34)}$$

$$\dot{D} = 34 \times \frac{\mu_m/\rho_m}{\mu_a/\rho_a} \times \dot{X}\ \text{Gy/s}.$$

μ_m is the linear energy absorption coefficient of the medium and
ρ_m is the density of the medium.

μ_a is the linear energy absorption coefficient for air for the photon energy and
ρ_a is the density of air.

Does-Exposure Relationship

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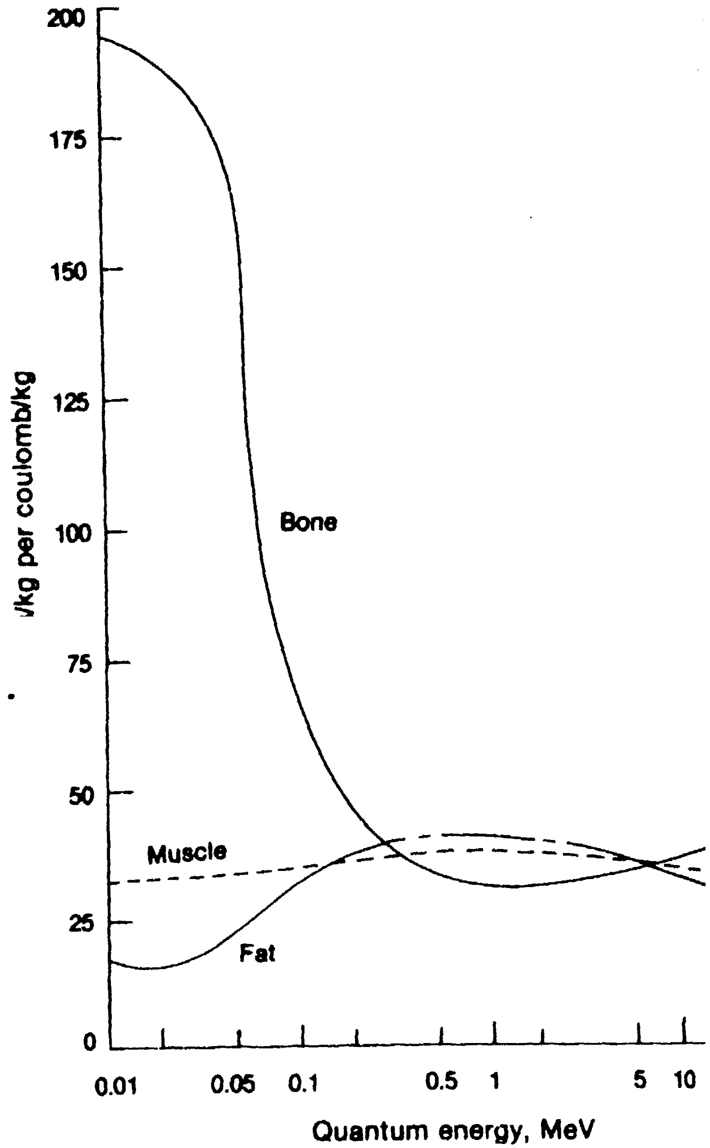
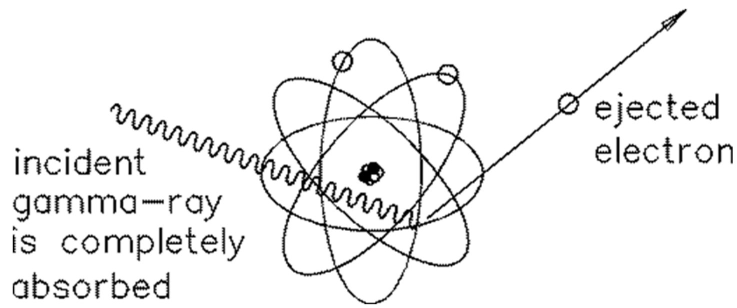


FIGURE 6.6. Energy absorption per X unit (coulomb per kilogram) exposure for several tissues. (Adapted from O. Glasser, *Medical Physics*, Vol. II. Yearbook Publishers, Chicago, IL, 1950. By permission.)

Photoelectric Effect

In photoelectric process, an incident photon transfer its energy to an orbital electron, causing it to be ejected from the atom.



$$E_{e^-} = h\nu - E_b$$

h is the Planck's constant

ν is the frenquency of the photon

- Photoelectric interaction is with the atom in a whole and can not take place with free electrons.
- Photoelectric effect creates a vacancy in one of the electron shells, which leaves the atom at an excited state.

Photoelectric Effect Cross Section

Probability of photoelectric absorption per atom is

$$\sigma \propto \begin{cases} \dfrac{Z^4}{(hv)^{3.5}} & low\ energy \\ \dfrac{Z^5}{(hv)^{3.5}} & high\ energy \end{cases}$$

- ***The interaction cross section for photoelectric effect depends strongly on Z.***
- ***Photoelectric effect is favored at lower photon energies. It is the major interaction process for photons at low hundred keV energy range.***

Page 49, Radiation Detection and Measurements, Third Edition, G. F. Knoll, John Wiley & Sons, 1999.