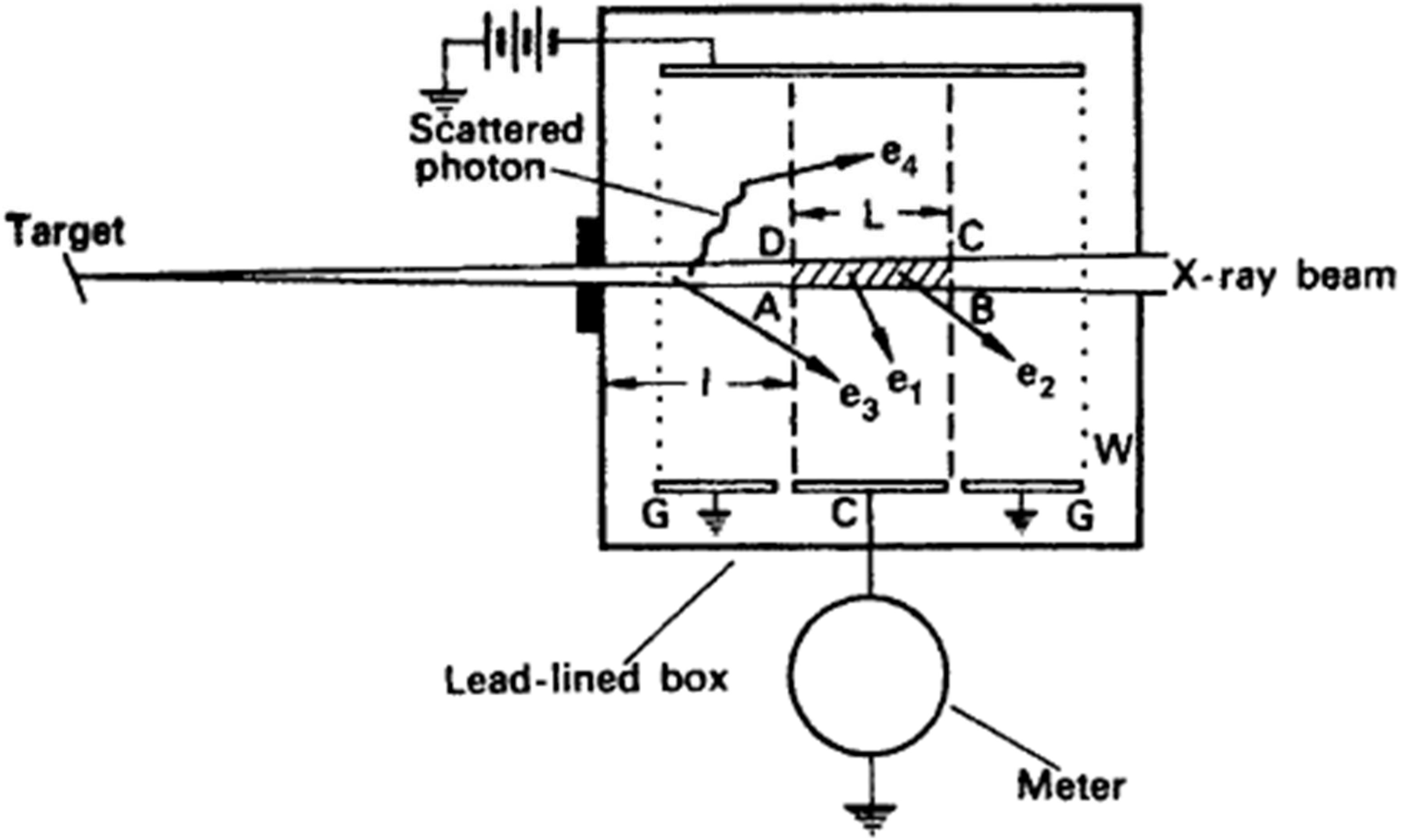
Radiation dosimetry

Exposure Measurement: The Free Air Chamber

The operational definition of the exposure unit can be satisfied by the instrument shown in Figure 1. The X-ray beam enters through the portal and interacts with the cylindrical column of air defined by the entry port diaphragm. All the ions resulting from interactions between the X-rays and the volume of air (A–B–C–D), which is determined by the intersection of the X-ray beam with the electric lines of force fromt he edges of the collector plate C, is collected by the plates, causing current to flow in the external circuit. Most of these collected ions are those produced as the primary ionizing particles lose their energy by ionizing interactions as they pass through the air. (The primary ionizing particles are the Compton electrons and the photoelectrons resulting from the interaction of the x-rays (photons) with the air.) The guardring G and the guard wires W help to keep these electric field lines straight and perpendicular to the plates. The electric field intensity between the plates is on the order of 100 V/cm—high enough to collect the ions before they recombine but not great enough to accelerate the secondary electrons produced by the primary ionizing particles to ionizing energy. The guard wires are connected to a voltage-dividing network to ensure a uniform potential drop across the plates. The number of ions collected because of X-ray interactions in the collecting volume is calculated from the current flow and the exposure rate, in roentgens per unit time, is then computed

.For the exposure unit to be measured in this way, all the energy of the primary electrons must be dissipated in the air within the meter. This condition can be satisfied by making the air chamber larger than the maximum range of the primary electrons. (For 300-keV X-rays, the spacing between the collector plates is about 30 cm and the overall box is a cube of about 50-cm edge.)



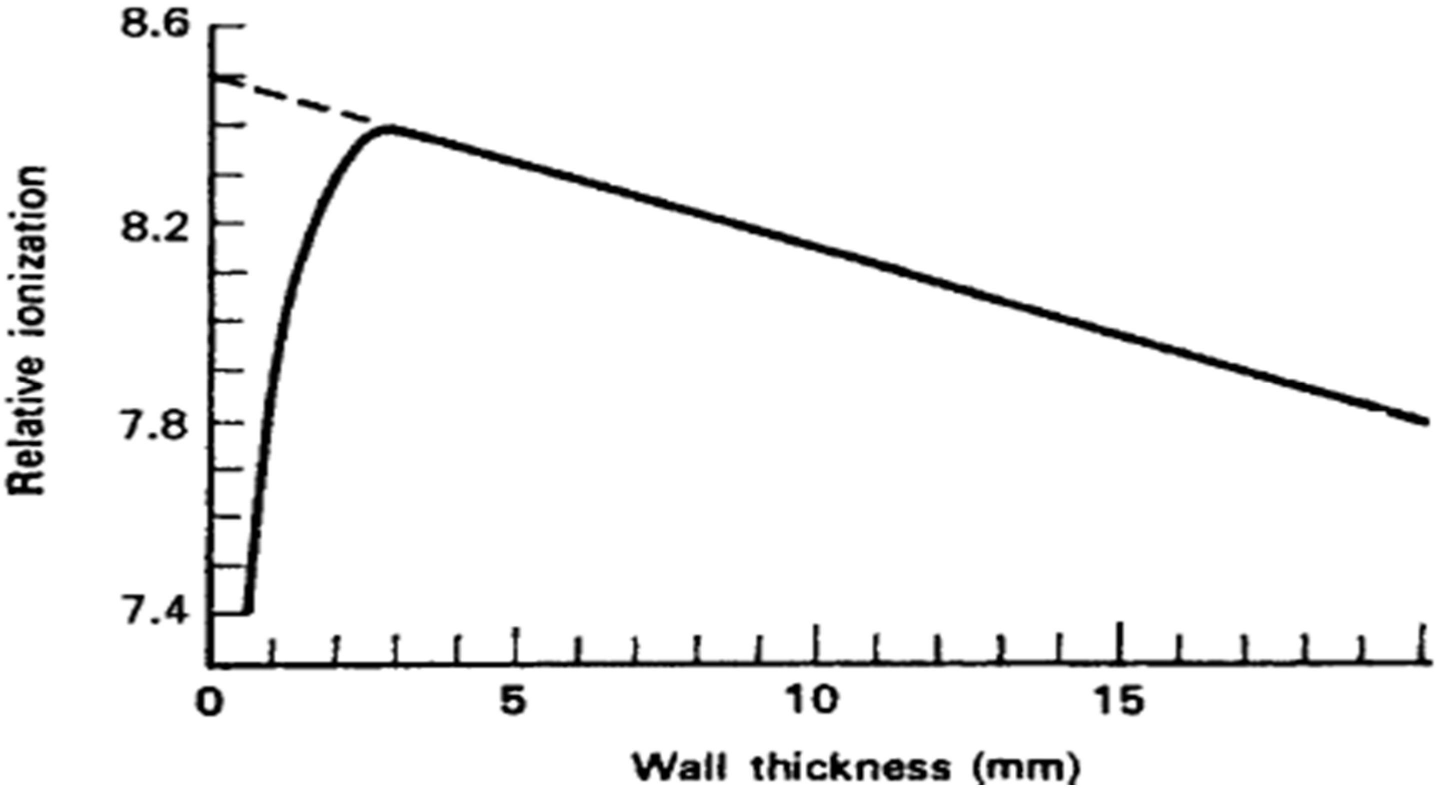
Example

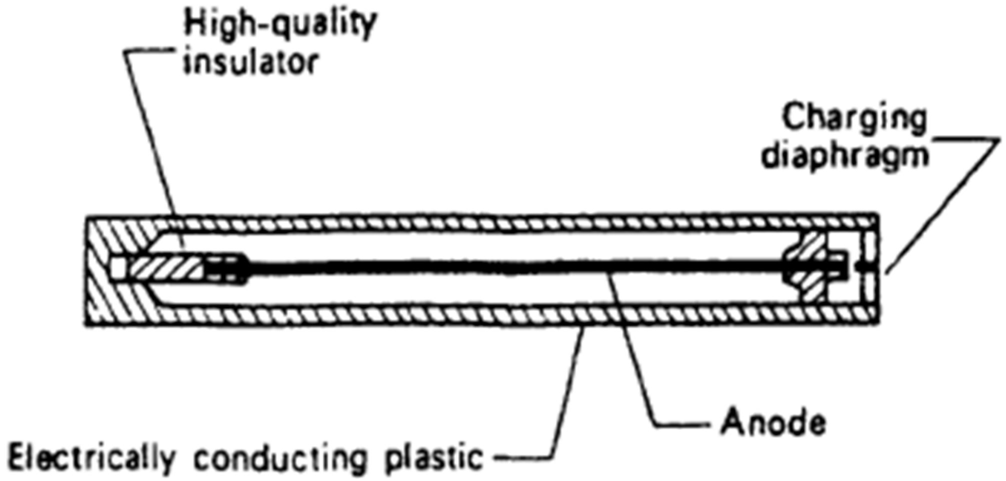
The opening of the diaphragm in the entrance port of a free air ionization chamber is 1 cm in diameter, and the length AB of the sensitive volume is 5 cm. A 200-kV X-ray beam projected into the chamber produces a steady current in the external circuit of 0.01 μA. The temperature at the time of the measurement was 20 ◦C and the pressure was 750 mm Hg. What is the exposure rate in this beam of X-rays?

Exposure Measurement: The Air Wall Chamber

The free air ionization chamber described above is practical only as a primary laboratory standard. For field use, a more portable instrument is enquired. Such an instrument could be made by compressing the air around the measuring cavity. If this were done, then the conditions for defining the exposure unit would continue to be met. In practice, of course, it would be quite difficult to construct an instrument whose walls were made of compressed air. However, it is possible to make an instrument with walls of “air-equivalent” material—that is, a wall material whose-ray absorption properties are very similar to those of air. Such a chamber can be built in the form of an electrical capacitor; its principle of operation can be explained with the aid of Figure 2.The instrument consists of an outer cylindrical wall, about 4.75-mm thick, made of electrically conducting plastic. Coaxial with the outer wall, but separated from it by a very high-quality insulator, is a center wire. This center wire, or central anode, is positively charged with respect to the wall. When the chamber is exposed to X-radiation or to gamma radiation, the ionization, which is produced in the measuring cavity as a result of interactions between photons and the wall, discharges the condenser, thereby decreasing the potential of the anode. This decrease in the anode voltage is directly proportional to the ionization produced in the cavity, which in turn is directly proportional to the radiation exposure. For example, consider the following instance:

A chamber built according to this principle is called an “air wall” chamber. When such a chamber is used, care must be taken that the walls are of the proper thickness for the energy of the radiation being measured. If the walls are too thin, an insufficient number of photons will interact to produce primary electrons; if they are too thick, the primary radiation will be absorbed to a significant degree by the wall and an attenuated primary-electron fluence will result.The determination of the optimum thickness may be illustrated by an experiment in which the ionization produced in the cavity of an ionization chamber is measured as the wall thickness is increased from a very thin wall until it becomes relatively thick.When this is done and the cavity ionization is plotted against the wall thickness, thecurve shown in Figure 3 results. Since the cavity ionization is caused mainly by primary electrons resulting from photon (gamma-ray) interactions with the wall, increasing the wall thickness allows more photons to interact, thereby producing more primary electrons, which ionize the gas in the chamber as they traverse the cavity. However, when the wall thickness reaches a point where a primary electron produced at the outer surface of the wall is not sufficiently energetic to pass through the wall into the cavity, the ionization in the cavity begins to decrease. The wall thickness at which this just begins is the equilibrium wall thickness,


8.6
8.2
7.8
7.4
Relative ionization
0
5
10
15
Wall thickness (mm)


High-quality insulator
Charging diaphragm
Anode
Electrically conducting plastic

Absorbed Dose Measurement: Bragg–Gray Principle

If a cavity ionization chamber is built with a wall material whose radiation absorption properties are similar to those of tissue, then, by taking dvantage of the Bragg–Gray principle, an instrument can be built to measure tissue dose directly. According to the Bragg–Gray principle, the amount of ionization produced in a small gas-filled cavity surrounded by a solid absorbing medium is proportional to the energy absorbed by the solid. Implicit in the practical application of this principle is that the gas

cavity be small enough relative to the mass of the solid absorber to leave the angular and velocity distributions of the primary electrons unchanged. This requirement is fulfilled if the primary electrons lose only a very small fraction of their energy in traversing the gas-filled cavity. If the cavity is surrounded by a solid medium of proper thickness to establish electronic equilibrium, then the energy absorbed per unit mass of wall, dE_m/dM_m, is related to the energy absorbed per unit mass of gas in the cavity,

- dE_g/dM_g, by

$dE_m/dM_m = S_m/S_g \times dE_g/dM_g$, ---------(b)

where

S_m is the mass stopping power of the wall material and

S_g is the mass stopping power of the gas.

Since the ionization per unit mass of gas is a direct measure of

dE_g/dM_g

(b) can be rewritten as

$dE_m d/M_m = \rho_m \times w \times J$

where

$\rho_m = S_m/g$,

W=the mean energy dissipated in the production of an ion pair in the gas, and

J=the number of ion pairs per unit mass of.. To determine the radiation absorbed dose, it is necessary only to measure the ionization J per unit mass of gas.

H.W

Calculate the absorbed dose rate from the following data on a tissue-equivalent chamber with walls of equilibrium thickness embedded within a phantom and exposed to ^{60}Co gamma rays for 10 minutes. The volume of the air cavity in the chamber is1 cm^3, the capacitance is 5 μF, and the gamma-ray exposure results in a decrease of 72 V across the chamber.

Kerma

In the case of indirectly ionizing radiation, such as X-rays, gamma rays, and fast neutrons, we are sometimes interested in the initial kinetic energy of the primary ionizing particles (the photoelectrons, Compton electrons, or positron–negatron pairs in the case of photon radiation and the scattered nuclei in the case of fast neutrons) that result from the interaction of the incident radiation with a unit mass of interacting medium. This quantity of transferred energy is called the kerma, K, measured in SI units in joules per kilogram, or grays. In the traditional system of units, it is measured in ergs per gram or in rads. Although kerma and dose are both measured in the same units, they are different quantities. The kerma is a measure of all the energy transferred from the uncharged particle (photon or neutron) to primary ionizing particles per unit mass, whereas absorbed dose is a measure of the energy absorbed per unit mass

Skin Contamination

When we refer to "skin dose", or to "shallow dose", we mean the dose to the viable, actively growing basal cells in the basement membrane of the skin. These cells are covered by a tissue layer of nonliving cells whose nominal thickness is 0.007 g/cm^2.

If the skin is contaminated with a radionuclide, we can calculate the dose rate to the contaminated tissue by assuming that 50% of the radiation goes down into the skin and 50% goes up and leaves the skin. If the skin is contaminated at a level of 1 Bq/cm^2 and the mean beta energy is $\bar{E}$ MeV, then the energy fluence rate, φ_b, to the basal cells at a depth of 0.007 g/cm^2 in the skin is

$$\varphi_b, \mathrm{J/cm^2/h} = 1\ \mathrm{Bq/cm^2} \times 1\ \mathrm{tps/Bq} \times 0.5 \times \bar{E}\ \mathrm{MeV/t} \times 1.6 \times 10^{-13}\ \mathrm{J/MeV} \times 3.6 \times 10^3\ \frac{\mathrm{s}}{\mathrm{h}} \times e^{-(\mu_{\beta,t}\ \mathrm{cm^2/g} \times 0.007\ \mathrm{g/cm^2})}.$$

The dose rate to the basal cells, $\dot{D}_b$, is

$$\dot{D}_b = \frac{\varphi_b \dfrac{\mathrm{J}}{\mathrm{cm^2/h}} \times \mu_{\beta,t} \dfrac{\mathrm{cm^2}}{\mathrm{g}}}{10^{-6}\ \dfrac{\mathrm{J/g}}{\mathrm{mGy}}} \frac{\mathrm{mGy}}{\mathrm{h}}.$$

After substituting Eq. (6.22) into Eq. (6.23) and simplifying, we have

$$\dot{D}_b = 2.9 \times 10^{-4} \bar{E} \times \mu_{\beta,t} \times e^{-(\mu_{\beta,t} \times 0.007)} \frac{\mathrm{mGy}}{\mathrm{h}}.$$

If the maximum beta energy E_m is given in MeV, then the beta absorption coefficients for air and for tissue are

$$\mu_{\beta,a}\ (\mathrm{air}) = 16\,(E_m - 0.036)^{-1.4}\ \frac{\mathrm{cm^2}}{\mathrm{g}}$$

and

$$\mu_{\beta,t}\ (\mathrm{tissue}) = 18.6\,(E_m - 0.036)^{-1.37}\ \frac{\mathrm{cm^2}}{\mathrm{g}}.$$

Gamma Emitters

For gamma-emitting isotopes, we cannot simply calculate the absorbed dose by assuming the organ to be infinitely large because gammas, being penetrating radiations, may travel great distances within the tissue and leave the tissue without interacting. Thus, only a fraction of the energy carried by photons originating in the radioisotope-containing tissue is absorbed within that tissue. Before the advent of computers that made complex computational methods possible, gamma ray doses from internal radionuclides were calculated by assuming the body to be made of spheres and cylinders and then using simple calculation techniques to determine internal dose. For example, in the case of a uniformly distributed gamma-emitting nuclide, the dose rate at any point p due to the radioactivity in the infinitesimal volume dV at any other point at a distance r from point p, as shown in Figure 6-8, is

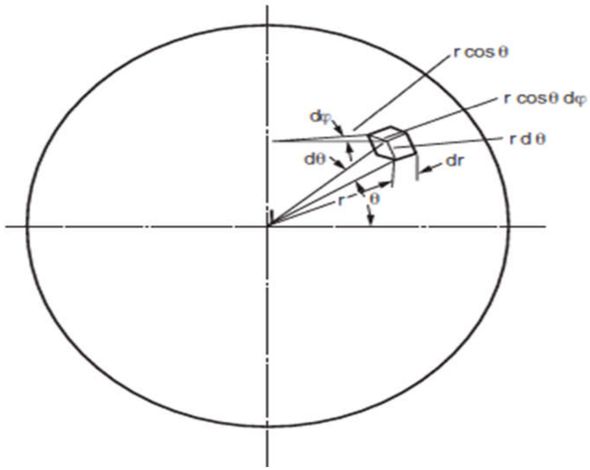
$$d\dot{D} = C\Gamma \frac{e^{-\mu r}}{r^2} dV, \tag{6.63}$$

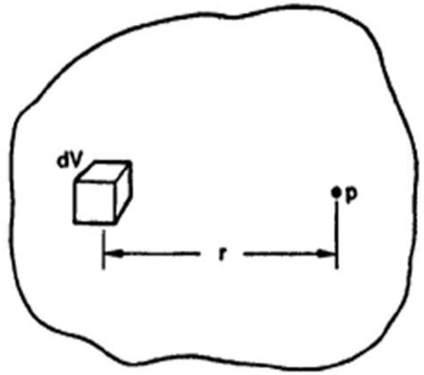
where C is the concentration of the isotope, Γ is the specific gamma-ray emission, and μ is the linear energy absorption coefficient. The dose rate at point p due to all

$$\dot{D} = C\Gamma \int_0^V \frac{e^{-\mu r}}{r^2} dV. \tag{6.64}$$

For the case of a sphere, the dose rate at the center (Fig. 6-9) is

$$\dot{D} = 4C\Gamma \int_{r=0}^{r=R} \int_{\theta=0}^{\theta=\pi/2} \int_{\varphi=0}^{\varphi=\pi} \frac{e^{-\mu r}}{r^2} \cdot r\,d\theta \cdot r\cos\theta\,d\varphi \cdot dr. \tag{6.65}$$





Integrating with respect to each of the variables, we have, for the dose rate at the center of the sphere,

$$\dot{D} = C\Gamma \cdot \frac{4\pi}{\mu}\left(1 - e^{-\mu R}\right). \qquad (6.66)$$

From an examination of Eqs. (6.63), (6.64), (6.65), and (6.66) it is seen that the factor that multiplies $C\Gamma$ depends only on the geometry of the tissue mass and hence is called the *geometry factor*.[1] The geometry factor g is defined by

$$g = \int_0^V \frac{e^{-\mu r}}{r^2} \mathrm{d}V. \qquad (6.67)$$

Equation (6.64) may therefore be rewritten as

$$D = C \times \Gamma \times g. \qquad (6.68)$$

The definition of g in Eq. (6.67) applies to a given point within a volume of tissue. In many health physics instances, we are interested in the average dose rate rather than the dose rate at a specific point. For this purpose, we may define an average geometry factor as follows:

$$\bar{g} = \frac{1}{V}\int g\,\mathrm{d}V. \qquad (6.69)$$

For a sphere,

$$\bar{g} = \frac{3}{4}(g)_{\mathrm{center}}. \qquad (6.70)$$

At any other point in the sphere at a distance d from the center, the geometry factor is given by

$$g_{\mathrm{p}} = (g)_{\mathrm{center}}\left[0.5 + \frac{1-(d/R)^2}{4(d/R)}\ln\frac{1+d/R}{|1-d/R|}\right]. \qquad (6.71)$$