2 Units of Radiation Protection

"All composed things tend to decay."

Buddha 563–483 B. C.

A large number of units has been proposed and used in the course of historical development and research in the field of radioactivity. Only those which have survived to today shall be used and defined here. I will introduce the modern units which are recommended by the International Commission on Radiological Protection (ICRP). In addition, I will also mention those units which are still in use in countries like in the USA, and give the relations to the ICRP-recommended units used in Europe and elsewhere.

1 becquerel (Bq) = 1 decay per second

1 curie (Ci) = 3.7 × 10^{10} Bq

The unit of activity is becquerel (Bq). 1 Bq is one decay per second. The old unit curie (Ci) corresponds to the activity of 1 g of radium-226:[1]

$$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}\ ,$$
$$1\,\mathrm{Bq} = 27 \times 10^{-12}\,\mathrm{Ci} = 27\,\mathrm{pCi}\ . \qquad (2.1)$$

In radioactive decays the number of decaying nuclei ΔN is proportional to the number of existing nuclei N and the observation time Δt. The number of nuclei decreases by decay. This fact gives the negative sign for ΔN. Therefore, one has

$$\Delta N \sim -N\ \Delta t\ . \qquad (2.2)$$

Since the decay rate changes in time it makes sense to use very small, indeed infinitesimal times $\mathrm{d}t$ and numbers $\mathrm{d}N$ (see Appendix Q),

$$\mathrm{d}N \sim -N\ \mathrm{d}t\ . \qquad (2.3)$$

decay constant

Starting from this relation one obtains the equation by introducing a constant of proportionality, namely, the decay constant λ,

[1] Because of the frequently occurring very large and very small numbers I will use throughout the notation using powers, e.g. $10^6 = 1\,000\,000$ and $10^{-6} = 0.000\,001$. A word of caution is in order here: A billion is in most parts of the world 10^9 while in some parts, e.g. in Germany, a billion is 10^{12}.

C. Grupen, *Introduction to Radiation Protection*,
Graduate Texts in Physics, DOI 10.1007/978-3-642-02586-0_2,
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$$\mathrm{d}N = -\lambda\, N\, \mathrm{d}t \ . \tag{2.4}$$

Such a differential equation can be solved generally by the so-called exponential function (see Appendix Q):

$$N = N_0\, \mathrm{e}^{-\lambda\, t} \ . \tag{2.5}$$

N_0 characterizes the number of nuclei existing at time $t = 0$, i.e. the number of originally existing atomic nuclei. The number $\mathrm{e} = 2.718\,28\ldots$ is the basis of the natural logarithm (see Appendix Q). Since the exponent of the exponential function has to be without dimension, the physical unit of the decay constant is second^{-1}. The decay constant λ is related to the *lifetime* of the radioactive source as

lifetime

$$\lambda = \frac{1}{\tau} \ . \tag{2.6}$$

One has to distinguish the half-life $T_{1/2}$ from the lifetime. The half-life is the time after which a half of the initially existing atomic nuclei has decayed. After another half-life a half of the remaining nuclei will have decayed, so that one is left with only one quarter of the original nuclei. That means, say, after 10 half-lives, there is still a fraction of 2^{-10} nuclei which has not decayed. Because of

half-life

$$N(t = T_{1/2}) = \frac{N_0}{2} = N_0\, \mathrm{e}^{-T_{1/2}/\tau} \ , \tag{2.7}$$

we will get, applying the rules of exponential functions and natural logarithms as explained in Appendix Q,[2]

$$\begin{aligned} \frac{1}{2} &= \mathrm{e}^{-T_{1/2}/\tau} \ , \\ \mathrm{e}^{T_{1/2}/\tau} &= 2 \ , \\ T_{1/2}/\tau &= \ln 2 \\ \text{or} \quad T_{1/2} &= \tau\ \ln 2 \ . \end{aligned} \tag{2.8}$$

The decay constant λ of an unstable radioactive nucleus is obtained as

$$\lambda = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} \ . \tag{2.9}$$

The activity A of a radioactive source characterizes the number of decays per second. Therefore, the activity A is equal to the change

activity

[2] The exponential function e^x and the natural logarithm $\ln x$ are operations which are available on most, even simple, non-scientific pocket calculators.

rate ΔN of existing atomic nuclei in the time Δt. Because a decreasing number of atomic nuclei represents a positive activity, one defines

$$A = -\frac{\Delta N}{\Delta t} \ . \tag{2.10}$$

For infinitesimal time intervals $\mathrm{d}t$ one has

$$A = -\frac{\mathrm{d}N}{\mathrm{d}t} \ . \tag{2.11}$$

With the help of Eq. (2.5) and the rules of calculus as presented in Appendix Q one obtains:

$$A = -\frac{\mathrm{d}}{\mathrm{d}t}(N_0 \, \mathrm{e}^{-\lambda t}) = \lambda \, N_0 \, \mathrm{e}^{-\lambda t} = \lambda \, N = \frac{1}{\tau} N \ . \tag{2.12}$$

Radioactive sources with a large lifetime τ (or, equivalently, half-life $T_{1/2}$) naturally have lower activities if a given number of nuclei is considered.

The activity in Bq does not say very much about possible biological effects. These are related to the deposited energy by the radioactive source in matter. The energy dose D (absorbed energy

energy dose

"I rather stick to the old activity unit.
'Micro-curie' sounds so much better
than 'mega-becquerel'!"

© by Claus Grupen

ΔW per mass unit Δm),

$$D = \frac{\Delta W}{\Delta m} = \frac{1}{\rho}\frac{\Delta W}{\Delta V} \tag{2.13}$$

(ρ – density, ΔV – volume element[3]), is measured in gray:

gray

$$1 \text{ gray (Gy)} = 1 \text{ joule (J)} \;/\; 1 \text{ kilogram (kg)} \;. \tag{2.14}$$

Gray is related to the old unit rad (radiation absorbed dose, 1 rad = 100 erg/g; still in use in the US) according to:[4]

1 Gy = 1 J/1 kg
1 Gy = 100 rad

$$1\,\text{Gy} = 100\,\text{rad} \;. \tag{2.15}$$

For indirectly ionizing radiation (i.e. photons and neutrons, but not electrons and other charged particles) a further quantity characterizing the energy dose, the 'kerma', is defined. Kerma is an abbreviation for "kinetic energy released per unit mass".[5] The kerma k is defined as the sum of the initial energies of all charged particles, ΔE, liberated in a volume element ΔV by indirectly ionizing radiation divided by the mass Δm of this volume element:

kerma

$$k = \frac{\Delta E}{\Delta m} = \frac{1}{\rho}\frac{\Delta E}{\Delta V} \;, \tag{2.16}$$

where ρ is the density of the absorbing material.

We see that kerma relates only to the energy transferred to the charged particles: it does not depend on which fraction of the energies of the charged particles is transported out of the volume by particle motion or by bremsstrahlung. Therefore, kerma is sometimes also called dose unit of the first interaction step. The unit of kerma is also gray (Gy).

dose unit of the first interaction step

Gray and rad describe the pure physical energy absorption. These units cannot easily be translated into the biological effect of radiation. Electrons, for example, ionize relatively weakly while, in contrast, α rays are characterized by a high ionization density. Therefore, biological repair mechanisms cannot be very effective in the latter case. The relative biological effectiveness (RBE) depends on the type of radiation, the radiation energy, the temporal distribution of the dose, and other quantities. The relative biological effectiveness is a factor by which we have to multiply the energy dose D

relative biological effectiveness

[3] A volume element, sometimes also called 'unit volume', is the differential element ΔV whose volume integral over some range in a given coordinate system gives the total volume V.

[4] 1 joule (J) = 1 watt second (W s) = $1\,\frac{\text{kg m}^2}{\text{s}^2} = 10^7\,\frac{\text{g cm}^2}{\text{s}^2} = 10^7$ erg

[5] Occasionally one also finds "kinetic energy released in matter (or: in material)".

of our chosen type of radiation giving the energy dose D_γ of X rays or γ rays which would have the same biological effect,

$$\mathrm{RBE} = D_\gamma / D \ . \tag{2.17}$$

Since it is not always known in radiation protection which biological effects one has to refer to in a specific case, instead of the complicated energy-, radiation-, and dose-rate-dependent RBE factors one uses the so-called quality factor Q to assess the effect of a physical energy deposition. This leads to the dose equivalent H,

dose equivalent

$$H = Q \ f \ D \ . \tag{2.18}$$

sievert

H is measured in sievert (Sv). The factor f considers further radiation-relevant factors such as the dose-rate dependence or reduced biological effects by a periodic irradiation. Such a technique of intermittent radiation is used in cancer therapy: if a patient should receive, say, a dose of 2 Sv to destroy a tumor, this dose is applied e.g. in ten separate fractions of 0.2 Sv, because in the intervals between these fractions the healthy tissue will recover more easily in contrast to the tumor tissue. A typical interval between subsequent fractions of irradiations is a day. All in all the product of the quality factor Q and the modifying factor f assesses the biological radiation effect of an absorbed dose D. Therefore, this product $q = Q \ f$ is called the weighting factor. Since both the quality factor Q and the correction factor f are dimensionless, so is the weighting factor q, and the unit of the equivalent dose is also J/kg.[6] The old unit rem (roentgen equivalent man), still in use in the United States, is related to sievert according to

weighting factor

1 Sv = 100 rem

$$1\,\mathrm{Sv} = 100\,\mathrm{rem} \ . \tag{2.19}$$

Nowadays the weighting factors q are called radiation weighting factors following a recommendation by the International Commission on Radiological Protection. These radiation weighting factors w_R depend on the type of radiation and for neutrons also on their energy. The most recent definition of radiation weighting factors following the recommendation of the International Commission on Radiological Protection is given in Table 2.1.

radiation weighting factors

For the radiation field R one gets the dose equivalent H_R from the energy dose D_R according to

[6] The energy dose D is measured in Gy and the equivalent dose H in Sv, therefore, the weighting factor q in principle has the unit Sv/Gy. However, both Gy and Sv have the same physical unit J/kg, where Gy only considers the physical effect while Sv also takes the biological effect into account.

"Atomic progress is quite educating!"

after Jupp Wolter

Table 2.1
Radiation weighting factors w_R[7]

type of radiation and energy range	**radiation weighting factor w_R**
photons, all energies	1
electrons and muons[8], all energies	1
neutrons $E_n < 10\,\mathrm{keV}$	5
neutrons $10\,\mathrm{keV} \le E_n \le 100\,\mathrm{keV}$	10
neutrons $100\,\mathrm{keV} < E_n \le 2\,\mathrm{MeV}$	20
neutrons $2\,\mathrm{MeV} < E_n \le 20\,\mathrm{MeV}$	10
neutrons with $E_n > 20\,\mathrm{MeV}$	5
protons, except recoil protons, $E > 2\,\mathrm{MeV}$	5
α particles, fission fragments, heavy nuclei	20

$$H_R = w_R\, D_R \ . \tag{2.20}$$

Figure 2.1 shows photographic records taken with a diffusion cloud chamber in normal air. They clearly demonstrate the strong ionizing effect of α particles from the radon decay chain (left). At the same time the weakly ionizing effect of decay electrons is visible. Their tracks in the diffusion cloud chamber are characterized by multiple scattering and large bending angles (right image).

Apart from these units another quantity is used for the amount of created charge, the roentgen (R). One roentgen is that radiation dose of X rays and γ rays, which liberates one electrostatic charge unit

roentgen

[7] The energy-dependent radiation weighting factor for neutrons can be approximated by the function $w_R = 5 + 17\,\mathrm{e}^{-\frac{1}{6}(\ln(2\,E_n))^2}$, where the neutron energy E_n is measured in MeV.

[8] Muons are short-lived elementary particles which are produced predominantly in cosmic radiation (see also Sect. 11.1).

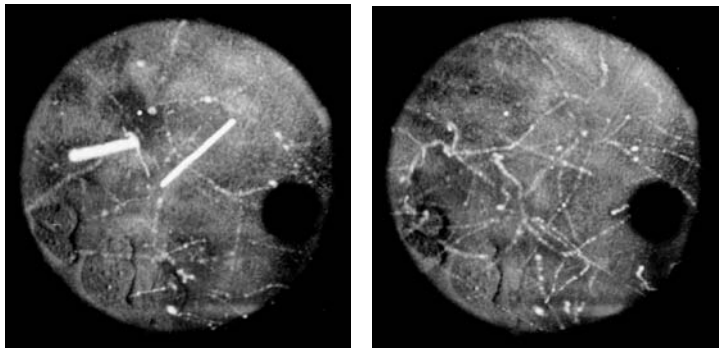


Figure 2.1
Tracks of α particles and electrons in a diffusion cloud chamber exposed to normal air in buildings. The different lengths and widths of α-particle tracks (left image) originate from projection effects

of electrons and one of ions in 1 cm^3 of air (at standard temperature and pressure).

ion dose

If the unit roentgen is expressed by the ion dose I in coulomb/kg, one obtains

$$1\,\mathrm{R} = 2.58 \times 10^{-4}\,\mathrm{C/kg}\ . \tag{2.21}$$

The tissue equivalent of roentgen is given by

$$1\,\mathrm{R} = 0.88\,\mathrm{rad} = 8.8\,\mathrm{mGy}\ . \tag{2.22}$$

For an approximate estimate of body doses for photon radiation it is generally sufficient to work out the photon equivalent dose according to

$$H_\mathrm{X} = \eta\, I_\mathrm{S}\ , \tag{2.23}$$

scale factor

where I_S is the standard ion dose in roentgen and the scale factor is given by

$$\eta = 38.8\,\mathrm{Sv\,(C/kg)^{-1}} = 0.01\,\mathrm{Sv/R}\ . \tag{2.24}$$

dose rate

To consider the time dependence of the dose equivalent or ion dose, we use the *dose rate*. The energy-dose rate is the change of the energy dose ΔD in the time Δt. Since the dose rate changes rapidly, particularly for radioactive sources with short half-life, it is advisable to use the differential notation (see Appendix Q). Depending on whether one prefers the notation $(\frac{\mathrm{d}}{\mathrm{d}t})$ introduced by Leibniz or the notation favored by Newton, as characterized by a dot over the quantity, one writes for the energy-dose rate

$$\frac{\mathrm{d}D}{\mathrm{d}t}\ \text{or, equivalently,}\ \dot{D}\ . \tag{2.25}$$

dose-equivalent rate

Correspondingly, also the dose-equivalent rate is given by

$$\frac{\mathrm{d}H}{\mathrm{d}t} \equiv \dot{H} \tag{2.26}$$

and the ion-dose rate by

ion-dose rate

$$\frac{\mathrm{d}I}{\mathrm{d}t} \equiv \dot{I} \ . \tag{2.27}$$

The physical units of these quantities are:

$$[\dot{D}] = \frac{\mathrm{J}}{\mathrm{kg\,s}} = \frac{\mathrm{W\,s}}{\mathrm{kg\,s}} = \frac{\mathrm{W}}{\mathrm{kg}} \ , \tag{2.28}$$

$$[\dot{H}] = [\dot{D}] \ , \tag{2.29}$$

$$[\dot{I}] = \frac{\mathrm{C}}{\mathrm{kg\,s}} = \frac{\mathrm{A\,s}}{\mathrm{kg\,s}} = \frac{\mathrm{A}}{\mathrm{kg}} \ . \tag{2.30}$$

$\dot{D}$ and $\dot{H}$ are therefore measured in watt per kilogram and $\dot{I}$ in ampere per kg.

The received dose can be related to the whole body (whole-body dose) or also only to specific parts of the body (partial-body dose). The dose equivalent that has accumulated within 50 years after a single incorporation[9] of radioactive substances in a certain organ or tissue is called '50-years dose-equivalent commitment'.

whole-body and partial-body dose

50-years dose-equivalent commitment

If a radiation exposure with an average per capita dose-equivalent rate $\overline{\dot{H}}(t)$ for a population group over an extended period has occurred, a dose-equivalent commitment is defined by

dose-equivalent commitment

$$H_\mathrm{f} = \sum \overline{\dot{H}}(t)\ \Delta t \ , \tag{2.31}$$

where one has to sum over the relevant time intervals Δt. If this dose rate $\overline{\dot{H}}(t)$ does not depend on the time, one has

$$H_\mathrm{f} = \overline{\dot{H}}\ t \ , \tag{2.32}$$

where t is the considered time interval.

The collective dose is the product of the total number of persons N by one person's average dose $\langle H \rangle$ in sievert or, more generally, the collective equivalent dose S is

collective dose

$$S = \sum_k P_k\ \langle H_k \rangle \ , \tag{2.33}$$

[9] When radioactive substances enter the human body, the radiation effects are different from those resulting from exposure to an external radiation source. Especially in the case of alpha radiation, which has a rather short range and normally never penetrates the skin, the exposure can be much more damaging after ingestion or inhalation. The terms ingestion and inhalation and the intake of radioactive compounds through wounds after accidents are usually subsumed under the expression *incorporation*.

Table 2.2
Tissue weighting factors w_T

organ or tissue	tissue weighting factor w_T
gonads	0.20
red bone marrow	0.12
colon	0.12
lung	0.12
stomach	0.12
bladder	0.05
chest	0.05
liver	0.05
esophagus	0.05
thyroid gland	0.05
skin	0.01
periosteum (bone surface)	0.01
other organs or tissue	0.05

where $\langle H_k \rangle$ is the per capita equivalent dose in an interval $H_k \ldots H_k + \Delta H_k$ and P_k the number of persons with radiation exposures in this interval.

effective dose equivalent

In many cases it is necessary to convert a partial-body dose into a whole-body dose. Therefore, a weighting factor w_T has to be attributed to the irradiated organs of the body. This effective dose equivalent is defined as

$$H_{\text{eff}} = \sum_{T=1}^{n} w_T H_T \ , \tag{2.34}$$

where H_T is the average dose equivalent in the irradiated organ or tissue and w_T is the weighting factor for the Tth organ or tissue.[10]

tissue weighting factor

For the purpose of radiation protection it is simply defined that the human has thirteen 'organs'. The weighting factors are normalized to 1 ($\sum w_i = 1$). These tissue weighting factors are compiled in Table 2.2.

radiation risk

It is assumed that the inhomogeneous irradiation of the body with an effective dose equivalent H_{eff} bears the same radiation risk as a homogeneous whole-body irradiation with $H = H_{\text{eff}}$.

The determination of the dose-equivalent rate by a pointlike radiation source of activity A can be accomplished using the following formula:

$$\dot{H} = \Gamma \frac{A}{r^2} \ . \tag{2.35}$$

In this equation r is the distance from the radiation source (in meters) and Γ a specific radiation constant which depends on the type and energy of the radiation. For β rays additionally the traveling

[10] In some cases the effective dose equivalent H_{eff} is also denoted with E in order to stress that in this case we are dealing with an effective dose.

Table 2.3
Dose constants Γ for some β- and γ-ray emitters[11]

radioisotope	**β dose constant** $\left(\frac{\text{Sv m}^2}{\text{Bq h}}\right)$
$^{32}_{15}$P	9.05×10^{-12}
$^{60}_{27}$Co	2.62×10^{-11}
$^{90}_{38}$Sr	2.00×10^{-11}
$^{131}_{53}$I	1.73×10^{-11}
$^{204}_{81}$Tl	1.30×10^{-11}

radioisotope	**γ dose constant** $\left(\frac{\text{Sv m}^2}{\text{Bq h}}\right)$
$^{41}_{18}$Ar	1.73×10^{-13}
$^{60}_{27}$Co	3.41×10^{-13}
$^{85}_{36}$Kr	3.14×10^{-16}
$^{131}_{53}$I	5.51×10^{-14}
$^{133}_{54}$Xe	3.68×10^{-15}
$^{137}_{55}$Cs	8.46×10^{-14}

dose constant

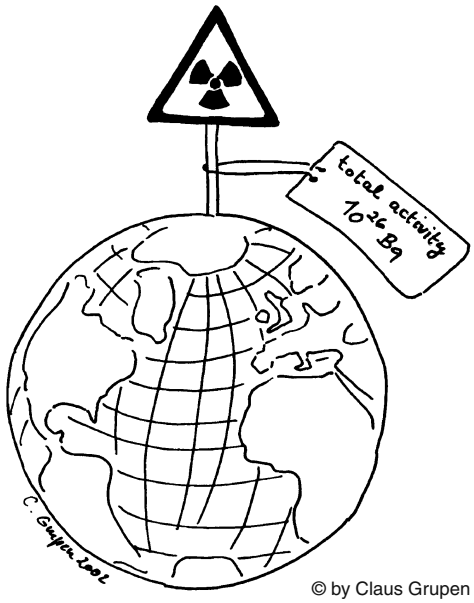
distance of electrons has to be considered. Table 2.3 lists the β and γ dose constants for some commonly used radiation sources. The $1/r^2$ dependence of the dose-equivalent rate is easily understood, if one considers that for isotropic emission (i.e. equally in all directions) the irradiated area for larger distances increases quadratically with distance r. The radiation emerging from the source has to pass through the surface of the virtual sphere (surface of sphere $= 4\pi r^2$), consequently the radiation intensity per unit area decreases like $1/r^2$ ('solid-angle effect').

$1/r^2$ law

The differences in the β and γ dose constants originate from the fact that electrons will normally deposit all of their energy in the body while the absorption power of the body for γ rays is much smaller. Differences in the β or γ dose constants for different radioisotopes have their origin in the different energy of the

energy absorption

[11] A chemical element is characterized by the number of positively charged nucleons (i.e. protons, with proton number $= Z$). Furthermore there are neutrons in the atomic nucleus which are essential for the binding of nuclei (neutron number $= N$). The atomic mass A is given by the sum of the proton and neutron numbers $Z + N$. Nuclei with fixed proton number but variable neutron number are called isotopes of the element with the atomic number Z. Isotopes which are radioactive are called radioisotopes. An isotope is characterized by the number of protons Z and neutrons N using the notation $^{A}_{Z}$*Element*. Since the name of the element is uniquely determined by Z, this index is frequently omitted, e.g. $^{137}_{55}$*Cesium* or ^{137}*Cesium*.



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emitted β and γ rays. As an example ^{137}Cs radiates a photon of energy 662 keV and ^{60}Co two γ rays with energies 1.17 MeV and 1.33 MeV. Consequently the γ dose constant for ^{60}Co is larger than for ^{137}Cs, even though the absorption coefficient for MeV photons is somewhat smaller compared to 662-keV photons.

A pointlike ^{137}Cs γ-ray emitter of activity 10 MBq produces a dose-equivalent rate of 0.846 µSv/h at a distance of 1 m. A ^{60}Co source of the same activity leads to a dose-equivalent rate of 3.41 µSv/h at the same distance. The dose-rate ratio of these two sources corresponds roughly to the ratio of the deposited energies.

dose-rate ratio

2.1 Supplementary Information

Example 1

contamination
ambient-dose rate

A radiation officer detects a contamination with ^{131}I in a medical laboratory which leads to an ambient-dose rate of 1 mSv/h. He decides to seal the room and wait until the activity due to the iodine contamination has decayed to such a level that the ambient-dose rate is only 1 µSv/h. For how long has the room to be sealed?

The half-life of the ^{131}I isotope is 8 days. The dose rate and consequently the activity should be reduced by a factor of 1000. The decay law

$$N = N_0 \, \mathrm{e}^{-t/\tau}$$

decay time constant

leads to a time dependence of the activity A like

$$A = A_0\, \mathrm{e}^{-t/\tau} \ ,$$

where A_0 is the initial activity. With $A/A_0 = 10^{-3}$ and $\tau = T_{1/2}/\ln 2$ one has

$$\exp\left(-\frac{t\ \ln 2}{T_{1/2}}\right) = 10^{-3}$$

and

$$t = \left(T_{1/2}/\ln 2\right)\ \ln 1000 = 79.7\,\mathrm{days}\ .$$

Consequently about 10 half-lives ($(1/2)^{10} = 1/1024$) are required to reach the necessary reduction factor.

Example 2

specific activity

A historical example for the specific activity leads to the definition of the old unit *curie*:

The half-life of ^{226}Ra is 1600 years. This leads to the specific activity (i.e. the activity per gram) of:

$$A^* = \lambda\, N = \frac{\ln 2}{T_{1/2}}\,\frac{N_\mathrm{A}}{M_\mathrm{Ra}} = \frac{\ln 2}{1600\,\mathrm{yr}}\,\frac{6.022\times 10^{23}}{226}$$
$$= 3.7\times 10^{10}\,\mathrm{Bq} = 1\,\mathrm{curie}\ .$$

(N_A is the Avogadro constant and M_Ra the atomic weight of ^{226}Radium, $1\,\mathrm{yr} = 3.1536\times 10^7$ s.)

Example 3

modified dose quantities

The radiation units presented so far have been recommended by the International Commission on Radiological Protection (ICRP). In addition, also the International Commission on Radiation Units and Measurement (ICRU) has proposed a slightly modified concept of dose quantities in the field of radiation protection. These quantities differ from the units presented so far by higher specialization and stronger formalization. These specialized dosimetric units are frequently used in national radiation-protection regulations.

radiation field

If in a specific tissue, organ, or part of the body, T, the energy dose $D_{T,R}$ is caused by a radiation field of type R, then the equivalent or organ dose is obtained by using the radiation weighting factor w_R as follows:

$$H_{T,R} = w_R\ D_{T,R}\ , \tag{2.36}$$

where w_R is the radiation weighting factor given in Table 2.1.

radiation quality

Equation (2.36) defines the partial-body doses T for a given radiation field R. If several different types of radiation (α, β, γ, n) work together, the corresponding partial-body dose is given by

$$H_T = \sum_R H_{T,R} = \sum_R w_R\ D_{T,R}\ . \tag{2.37}$$

The effective dose equivalent $H_{\text{eff}} = E$ can be derived from Eq. (2.37) by weighting the different energy doses with the tissue weighting factors w_T, which have been presented in Table 2.2:

$$E = H_{\text{eff}} = \sum_T w_T \, H_T = \sum_T w_T \sum_R w_R \, D_{T,R} \ . \qquad (2.38)$$

operative units of personal dosimetry

Furthermore, dose units for penetrating external radiation (depositing most of their energy in the first 10 mm of tissue) and for radiation of low penetration depth (70 µm skin depth) have been introduced in many national radiation-protection regulations. In personal dosimetry these operative units are denoted with $H_{\text{p}}(10)$, $H_{\text{p}}(0.07)$.

depth dose

In the past these operative units had been determined with film badges (see Sect. 5.6). However, the measurement of the depth doses $H_{\text{p}}(10)$ and $H_{\text{p}}(0.07)$ with film badges is not very accurate. A precise value for the skin dose as derived from the penetration depth of the radiation can be obtained with more sophisticated dosimeters. Such a new type of dosimeter, called 'sliding-shadow' dosimeter, has been developed, which allows a reliable determination of the skin doses.[12] These dosimeters are optimized for a depth-dose determination and allow at the same time a determination of energy and angle of incidence of photons, and they can further discriminate between β and γ rays.

'sliding-shadow' method

The availability of this new measurement technique necessitated to convert the hitherto existing quantities $H_{\text{p}}(10)$ and $H_{\text{p}}(0.07)$ into the new quantities $H^*(10)$ and $H^*(0.07)$. The conversion factors depend on the photon energy and the angle of incidence. For environmental radiation, γ rays or X rays from X-ray tubes with accelerating voltages below 50 kV and above 400 kV the conversion factor is 1; i.e. the old and new depth doses are identical. For γ rays from radioactive sources which are frequently used as X-ray sources (e.g. ^{57}Co, ^{67}Ga, ^{75}Se, $^{99\text{m}}$Tc, ^{153}Gd, ^{153}Sm, ^{169}Yb, ^{170}Tm, ^{186}Re, ^{192}Ir, ^{197}Hg, ^{199}Au, ^{201}Tl, ^{241}Am) and for the radiation field of X-ray tubes operated with accelerating voltages between 50 kV and 400 kV, the conversion factors are $H^*(10)/H_{\text{p}}(10) = 1.3$ and $H^*(0.07)/H_{\text{p}}(0.07) = 1.3$. This means that the depth doses as determined with the old film badges have to be increased by 30%.

conversion factor for depth doses

More details on the new skin doses can be found in the article "New quantities in radiation protection and conversion coefficients"

[12] These 'sliding-shadow' dosimeters use a special arrangement of structured metal and plastic filters and directional indicators. In addition, β rays can be distinguished from γ rays, which is essential for a reliable individual depth-dose information. The different absorption coefficients of the filters used allow an accurate measurement of the skin dose over a wide energy range. The basic detector behind the arrangement of filters is still a sensitive film, like in the old film badge.

Proposal for a new unit for radiation protection

The common units for radiation doses (Gy, Sv) are not very persuasive for a broader audience. The layman also has difficulties to interpret a dose given in Gy or Sv. Even relatively low radiation exposures which can only be detected because of extraordinarily sensitive measurement devices (one can measure the decay of individual atomic nuclei without difficulty) occasionally lead to over-reactions in public discussions. It is, however, very important to express radiation levels, caused, for example, by CASTOR transports or nuclear power plants, in units which can be understood and interpreted by the layman. It is perfectly sufficient to appreciate the order of magnitude of a radiation exposure, i.e., in easily comprehensible and self-explaining units which can be judged upon intuitively.

Mankind has developed with permanent natural radiation caused by cosmic rays and terrestrial rays and by permanent incorporation by ingestion and inhalation of natural radioisotopes. There are no hints whatsoever that this radiation has created any biological defect, it may even have increased the biodiversity. The natural radiation dose is subject to regional variations, but the natural annual radiation dose does not fall below 2 mSv for anybody. This natural annual dose sets the scale on which to judge on additional radiation burdens by civilization, for example, by medical diagnosis.

It is therefore proposed to use this typical value of the inevitable annual dose (IAD) due to natural radiation as a scale against which additional radiation exposures should be judged in discussions in the public:[13]

$$\mathbf{1\,IAD = 2\,mSv}\ .$$

In these units the following table gives some typical radiation exposures.

type of radiation exposure	dose in IAD
X-ray of a tooth	0.005
radiation level by nuclear power plants	≤ 0.01/yr
CASTOR transport for accompanying persons	≤ 0.015
air flight London – New York	0.015
X-ray of the chest	0.05
mammography	0.25
scintigraphy of the thyroid gland	0.40
heavy smoker (more than 20 cigarettes per day)	0.50/yr
positron-emission tomography	4.0
computer tomography of the chest	5.0
limit for radiation-exposed persons in Europe	10
limit for radiation-exposed persons in the USA	25
maximum life dose for radiation-exposed persons in Europe	200
lethal dose	2000
local cancer therapy	$\approx 30\,000$

Based on these numbers everybody can judge independently on the realistic risk caused by radiation exposures.

[13] G. Charpak and R. L. Garwin proposed a similar unit; they set the scale by the body-intrinsic radioactivity which leads to an annual radiation dose of 0.2 mSv. They named this dose 1 DARI, where the acronym DARI stands for Dose Annuelle due aux Radiations Internes. Europhysics News 33/1, p. 14 (2002).

published by the British Committee on Radiation Units and Measurements (see also J. Soc. Radiol. Prot. Vol. 6, p. 131–136, (1986)).

Summary

The essential units of radiation protection are becquerel (Bq) for the activity, gray (Gy) for the purely physical energy deposition per mass unit, and sievert (Sv) for the energy dose weighted by the biological effectiveness. A further characteristic quantity for a radioactive isotope is its half-life $T_{1/2}$. Radioisotopes with large half-lives are associated with a low activity, and those with short half-lives with a high one. The activity alone is not a good measure for a possible biological damage. This damage depends on the type of emitter and, of course, on the distance to the radiation source.

2.2 Problems

Problem 1

A radioactive material possesses an approximately constant gamma activity of 1 GBq. Per decay 1.5 MeV are liberated. What is the daily energy dose if the ionizing radiation is absorbed in an amount of material of mass $m = 10\,\mathrm{kg}$?

Problem 2

In a nuclear physics laboratory a researcher has inhaled dust of a ^{90}Sr isotope by accident, which has lead to a dose rate of $1\,\mu\mathrm{Sv/h}$ in his body. The physical half-life of ^{90}Sr is 28.5 yrs, the biological half-life for retention in the lung (see Chap. 13, Page 217) is only 80 days. How long does it take until the dose rate has decreased to $0.1\,\mu\mathrm{Sv/h}$?
(The biological half-life is defined by the time until 50% of the activity is eliminated by the body by normal biological activity.)

Problem 3

At a distance of 2 m from a pointlike ^{60}Co source a dose rate of $100\,\mu\mathrm{Sv/h}$ is measured. What is the activity of the source?
(To solve this problem you should use information from Figs. 3.4 and 4.4.)

Problem 4

nuclear medicine

The radioisotope technetium 99m is frequently used in nuclear medicine. ^{99m}Tc is a metastable state of ^{99}Tc, it has a half-life of 6 h. What kind of activity has a patient who was administered an activity of 10 MBq ^{99m}Tc for a kidney examination after a period of two days? For this estimate one can assume that the effective half-life can be approximated by the physical half-life.