

Natural Sources of Ionizing Radiation

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Many of our students seem to have well-defined but not necessarily well-founded opinions on the biological effects of ionizing radiation. During discussions of nuclear transformations in introductory chemistry and physics courses we might be able to help these students better understand the magnitude of these effects, and perhaps sort out the plethora of units with which radiation measurements are expressed.

Units of Radiation Measurement

There are four fundamentally different approaches to the measurement of ionizing radiation, and at least eight different units in which these measurements can be expressed. One can determine the activity of the source in units of disintegrations per second, curies, or becquerels; the radiation to which an object is exposed in roentgens; the radiation absorbed by the object in units of rads or grays; or the radiation dose in units of rems or sieverts.

The curie (Ci), originally defined as the activity of one gram of ²²⁶Ra, is now defined as 3.700×10^{10} disintegrations per second. The becquerel (Bq), which is 1 disintegration/s, is the SI unit for activity, and 1 curie is therefore 3.700×10^{10} Bq. The roentgen (R) is the quantity of X- or γ -radiation needed to produce 1 esu of charge per cm³ of dry air at STP. The roentgen, however, is limited to use with X- or γ -radiation with an energy less than 3 Mev.

The radiation absorbed dose or rad is the amount of absorbed radiation that deposits 100 ergs per gram or 0.01 J per kilogram of material. Unfortunately, equal doses of different forms of radiation produce different biological effects. The rem was therefore defined as the amount of absorbed radiation that produces the same biological effect as one rad of therapeutic X-rays, or the product of the absorbed dose in rads times the relative biological effectiveness (RBE) of the radiation. Since the RBE of various forms of radiation is difficult to measure with precision, health physicists prefer to define the rem as the product of rads times a quality factor (QF) related to the linear energy transfer (LET) of the radiation, the rate at which energy (in kev) is dissipated per unit of path length (in μm). Radiation with a high LET is assigned a large QF since the RBE is known to increase with LET except at very high values of LET. Typical values of the quality factor are given below.

| Radiation | Quality Factor |
|-----------------------------------|----------------|
| X- or γ -rays | 1 |
| $\beta^- > 0.03$ Mev | 1 |
| $\beta^- < 0.03$ Mev | 1.7 |
| thermal neutrons | 3 |
| fast neutrons or protons | 10 |
| α -particles or heavy ions | 20 |

The gray (Gy) and sievert (Sv) are the SI replacements for the units of rads and rems, respectively. The gray is defined as 1

joule of absorbed radiation per kilogram of body weight, and there are therefore 100 rads in 1 Gy.

The confusion that results from this abundance of units is amplified by the absence of simple conversions between these units of measurement. It is not easy to convert from measurements of the radiation to which an object is exposed to estimates of the radiation absorbed, since the energy absorbed depends upon the effective atomic number of the absorbing material and the energy of the radiation. When 1-g samples are exposed to 1 R of X-rays at 0.1 Mev, for example, air absorbs 0.87 rems, soft tissue absorbs 0.95 rems, and bone absorbs 1.75 rems of radiation. Nor is it easy to convert from measurements of activity to estimates of the radiation absorbed. The activities of the ¹⁴C and ⁴⁰K in the human body, for example, are roughly the same, 0.1 μCi , and yet the radiation dose equivalent in mrem/y for ⁴⁰K is almost 20 times as large.

We can, however, estimate the radiation dose absorbed if we know the activity of the source, the mode or modes of decay of the radionuclide, the energy of the emitted radiation, and the relative biological effectiveness or quality factor of this radiation.

Calculations of Activity from Abundance Data

The activity can be calculated from the weight of the sample and the isotopic abundance of the radionuclide. The average human, for example, weighs 70 kg and contains 140 g of potassium. Since the isotopic abundance of ⁴⁰K is 0.0117%,³ there are 16.4 mg of ⁴⁰K or 2.47×10^{20} atoms of ⁴⁰K in the average body. From the number of atoms of ⁴⁰K and the half-life of 1.28×10^9 years,

$$-\frac{dN}{dt} = kN = \left(\frac{0.6931}{t_{1/2}}\right) N \quad (1)$$

we can calculate an activity for the ⁴⁰K in the average body of 1.34×10^{11} disintegrations per year, or 0.115 μCi . Assuming 1.6×10^4 g of carbon in the average human body, an isotopic abundance for ¹⁴C of 1 part in 10^{12} , and a half-life of 5730 years, we obtain an activity of 0.08 μCi for ¹⁴C.

Calculations of the Radiation Dose Equivalent

Estimates of the radiation absorbed from in vivo sources of ionizing radiation can be made from the activity of the radionuclide. For α -emitters such as ²¹⁰Po, one can safely assume that all of the energy of the α -particle is absorbed by the neighboring tissue. Thus, if the ²¹⁰Po α -particle energy is 5.30 Mev and the activity of ²¹⁰Po in the average male's liver is 27 pCi,² approximately 2.7×10^{-5} J is absorbed by the liver per year. Averaged over the 1.8-kg mass of the liver, this is equal to 1.5×10^{-5} J/kg/y or 1.5 mrad/y. Assuming a quality factor of 20 for α -radiation yields a radiation dose equivalent to the liver of roughly 30 mrem/y.

Calculations for β^- (negatron) emitters such as ¹⁴C are complicated by the fact that the β^- particles are not monoenergetic. Whereas the energy of the ¹⁴C β^- is given as 0.156 Mev, negatrons are in fact emitted over a broad range of energies from almost zero to a maximum of 0.156 Mev. During negatron emission the nucleus emits two particles, a β^- and an antineutrino ($\bar{\nu}$), and the energy released is partitioned between these two particles. Since the neutrino escapes from the body, the effective energy of this decay process is signifi-

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² All data on elemental abundances, body weights, and effective radii of body organs were taken from International Commission on Radiological Protection, "Report of the Task Group on Reference Man," ICRP Publ. 23, Pergamon Press, Oxford, 1975.

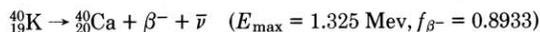
³ Data on the abundances of radionuclides, their decay schemes, the energies emitted, and the fraction of the nuclei which decay by a given scheme were taken from Lederer, C. M., and Shirley, V. S., "Table of Isotopes," 7th ed., John Wiley and Sons, New York, 1978.

cantly less than the maximum energy. The average or effective β^- energy is roughly one-third of the maximum energy, and it can be estimated from eqn. (2),

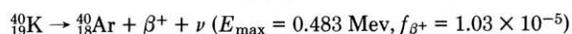
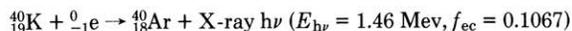
$$E_{\beta^-} = (f_{\beta^-}) (0.33 E_{\max}) \left(1 - \frac{\sqrt{Z}}{50}\right) \left(1 + \frac{\sqrt{E_{\max}}}{4}\right) \quad (2)$$

where f_{β^-} is the fraction of the nuclei that decay by β^- emission, E_{\max} is the maximum energy, and Z is the atomic number of the parent nuclide.⁴ Since ^{14}C is a pure β^- emitter, f_{β^-} is 1.00, and the effective energy is 0.0441 Mev. If this energy is dissipated within the body, the energy absorbed per kilogram of body weight per year assuming an activity for ^{14}C of 0.8 μCi is roughly 1×10^{-5} J/kg/y or 1 mrem/y.

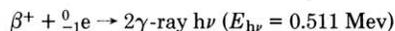
Estimates of the radiation dose from ^{40}K are complicated by the different modes of decay for this nuclide. ^{40}K is a β^- emitter,



that also undergoes both electron capture and positron emission.



Calculations for ^{40}K must therefore take into account the energy released during negatron emission, the X-ray photon that accompanies electron capture, the energy of the β^+ , as well as the two gamma-ray photons emitted when the positron at rest is annihilated by combination with an electron.



The average or effective β^- energy for ^{40}K , using eqn. (2), is 0.459 Mev. The effective energy of the X-rays emitted during electron capture is given by

$$E_{\text{ec}} = (f_{\text{ec}}) (E_{h\nu}) (1 - e^{-\mu_{\text{en}}x}) \quad (3)$$

where $E_{h\nu}$ is the energy of the X-ray photon, μ_{en} is the linear energy absorption coefficient, x is the effective radius of the body organ containing the radioisotope, and $(1 - e^{-\mu_{\text{en}}x})$ gives the fraction of the photons absorbed by the body. The effective radius (x) of the human body is about 30 cm,² and μ_{en} for a 1.46 Mev photon is 0.0283 cm^{-1} .⁵ The effective X-ray energy is therefore 0.0891 Mev.

The effective energy for β^+ emission is given by

$$E_{\beta^+} = (f_{\beta^+}) [(0.33 E_{\max}) \left(1 + \frac{\sqrt{E_{\max}}}{4}\right) + 2(0.511) (1 - e^{-\mu_{\text{en}}x})] \quad (4)$$

where the first term estimates the energy dissipated as the β^+ comes to rest, and the second term estimates the energy absorbed from the pair of γ -rays emitted when the β^+ at rest annihilates an electron.

The frequency of β^+ emission for ^{40}K is so small that the effective energy for ^{40}K decay is the sum of the energies from negatron emission and electron capture, or 0.548 Mev. When 0.115 μCi of activity is transformed into d/y and multiplied by this energy we obtain an estimate of the energy absorbed per kilogram of total body weight per year of 1.68×10^{-4} J/kg/y or 16.8 mrem/y.

The same techniques can be used to estimate the dose from ingested radioisotope contaminants. For example, if the average body burden from ^{137}Cs produced as a result of fallout from atmospheric weapons tests reached a maximum of 14.0 nCi in the third quarter of 1961,⁶ and ^{137}Cs emits a β^- with an energy of 0.512 Mev, the radiation dose is roughly 0.6 mrem/y. If the level of ^{131}I contamination of milk after the accident at Three Mile Island was less than 41 pCi per liter,⁷ and ^{131}I is a β^- emitter with a maximum energy of 0.606 Mev, the radiation absorbed from drinking a liter a day of this contaminated milk is roughly 0.002 mrem/y.

Sources of Ionizing Radiation

The average whole-body exposure levels for a number of sources of ionizing radiation have been estimated.⁸

| Source | Per Capita Dose |
|--|-----------------|
| natural background ⁹ | 82 mrem/y |
| medical X-rays | 77 mrem/y |
| nuclear test fallout | 5 mrem/y |
| consumer and industrial products ¹⁰ | 5 mrem/y |
| nuclear power ¹¹ | <1 mrem/y |

Contributions to the natural background of 82 mrem/y come from both external and internal sources. External sources include cosmic rays and terrestrial radiation such as the γ -emitters in rocks and soils. The average dose from cosmic rays, corrected for natural shielding effects, is 28 mrem/y,¹² and the γ -ray dose, once again corrected for natural shielding, averages 26 mrem/y.¹³ Internal sources of radiation, which contribute the remaining 28 mrem/y to the average natural background, include radionuclides that enter the body through respiration (e.g., ^{14}C , ^{85}Kr , $^{220,222}\text{Rn}$) or through the food chain. Internal sources can also be divided between nuclides such as ^3H , ^{14}C , ^{40}K , and ^{226}Ra which have been present throughout the evolution of the species, and isotopes such as ^{85}Kr , ^{90}Sr , ^{131}I , and ^{137}Cs whose contribution to the total body burden has increased significantly during the atomic era.

^{14}C and ^{40}K are the dominant contributors to the 20 mrem/y for whole-body exposure to internal sources of β^- and γ -radiation, although other sources such as ^3H , ^{87}Rb , ^{90}Sr , ^{131}I , and ^{137}Cs exist. Another 8 mrem/y comes from α sources such as ^{210}Po , $^{220,222}\text{Rn}$, $^{226,228}\text{Ra}$, and $^{234-238}\text{U}$. Three special considerations should be borne in mind when assessing the effect of α -radiation. First, the biological effect of α -radiation is 10–20 times as severe as β^- and γ -radiation of the same energy. Second, whereas ^{14}C and ^{40}K are distributed more or less uniformly throughout the body, many α -emitters concentrate in bone. Third, the estimate of 82 mrem/y for natural back-

⁴ Equations for the calculation of the average or effective energies of negatron emission, positron emission, and X-ray or γ -ray absorption were adapted from the report of ICRP Committee II on permissible doses for internal radiation, *Health Physics*, **3**, 1 (1960).

⁵ μ_{en} varies with the energy of the photon and the material that absorbs the radiation. It can be estimated from a table of μ_{en} /density on p. 140 of the "Radiological Health Handbook," U.S. Department of Health, Education, and Welfare, Consumer Protection and Environmental Health Service, 2nd ed., 1970, by assuming that the density of soft tissue is 1 g/cm³.

⁶ Richmond, C. R., and Furchner, J. E., *Radiat. Res.*, **32**, 538 (1967).

⁷ *Science*, **204**, 280 (1979).

⁸ All data on average radiation dose equivalent exposure were taken from: Committee on the Biological Effects of Ionizing Radiation, "The Effects on Population of Exposure to Low Levels of Ionizing Radiation: 1980," (commonly known as BEIR III), National Academy Press, Washington, DC, 1980.

⁹ The level of natural background radiation reported in BEIR III varies considerably, from 73 mrem/y in New Haven, CT, to 197 mrem/y in Colorado Springs, CO.

¹⁰ BEIR III reports an average dose equivalent of 0.7 mrem/y from luminous wristwatches and clocks, 0.5 mrem/y for males from TV sets, and 3.5 mrem/y from construction materials. The dose equivalent to the bronchial epithelium from tobacco products has been estimated to be as high as 8,000 mrem/y.

¹¹ This estimate from BEIR III includes the release of radionuclides to the environment from the mining and milling of uranium, the fabrication of reactor fuels, the storage of radioactive wastes, and the operation of nuclear reactors.

¹² The dose from cosmic rays varies with both altitude and latitude, increasing from 26 mrem/y at sea level to 107 mrem/y at 10,000 ft, and increasing steadily from the equator to latitudes of 40–50°.

¹³ The γ -ray dose ranges from 15–35 mrem/y in the Atlantic and Gulf coastal plains to 75–140 mrem/y on the Colorado plateau.

ground radiation, or 28 mrem/y for in vivo sources of radiation, are the sum of either whole-body exposures or exposures to the reproductive organs, and the radiation dose exposure to localized portions of the body can be very much larger. For example, the dose from $^{226,228}\text{Ra}$ measured at the gonads is only 0.5 mrem/y, but the dose to the osteocytes is 35.4 mrem/y.

Biological Effects of Ionizing Radiation

An appreciation for the magnitude of the radiation absorbed per year due to natural or background radiation may

provide a basis for discussions of other sources of ionizing radiation, be they medical X-rays, consumer products, or the nuclear power industry. Optimists might note that exposure to a continuous lifetime of 1000 mrem/y is projected to result in 169 excess cancer deaths per million persons exposed in addition to the 170,000 cancer deaths in this population in the absence of such exposure.⁸ Pessimists might note that exposure to radiation produces genetic damage in the form of gene mutations and chromosome aberrations as well as inducing cancer, and, "that almost without exception, detectable mutations have been found to be deleterious—mildly or strongly—in their effects."⁸