Units of Radiation and Radioactivity

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Measurements, and the units in which the measurements are to be made, are important in any discussion of a scientific subject. We begin to know something about a physical quantity when we can measure it. If we are to assess the hazards associated with radioactivity, if we are to use the radiations for therapy, for biological research, and in industry, we must be able to measure the strength of our radioactive source, we must be able to measure the radiation dose received; and to do so, we must have units in which to make the measurements.

As in any growing and expanding science in which our knowledge is still limited, agreement on measurements made in different laboratories is not perfect, and as yet agreement on terminology and in the magnitudes of all units has not been reached. Some confusion results, but we can reduce such confusion by a knowledge of, and exactness in, the terms used.

Curie

Let us turn first to units for measuring the activity of a radioactive source. Determination of the absolute activity of radioactive samples is highly important in dose determinations and is based on the number of atoms disintegrating per second. Conventionally, the unit of activity or quantity of radioactive material is the curie. When the principal radioactive element in general use was radium, there were two well-defined units for expressing the quantity of radioactive material. One was simply a gram of radium, which could be determined by weighing. Amounts of radium were then determined by comparing the gamma radiation of the unknown sample with that of a carefully weighed standard, when conditions of filtration, instrument for measuring the radiation, and geometry all were the same.

Since in many cases radon is used in place of radium, a second unit named the curie was defined as that quantity of radon (0.66 mm.^{3} at 0° and 760 mm. Hg) in radioactive equilibrium with 1 gram of radium. In 1930, the curie was extended to include the equilibrium quantity of any decay product of radium—that quantity of a decay product of radium which has the same disintegration rate as a gram of radium, or that has the same number of atoms disintegrating per unit time as 1 gram of radium. Measurements of the absolute decay rate of radium are not in perfect agreement; hence, the number is not precisely known, and in 1930 the International Radium Standard Commission recommended using the value of 3.7×10^{10} disintegrations per second. (A millicurie corresponds to 3.7×10^{7} dis/sec.; 1 microcurie, to 3.7×10^{4} dis/sec.)

The curie has become widely adopted as a measure of the quantity of any radioisotope and not limited to members of the radium family as recommended by the commission. Thus, 1 mil-

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licurie of P^{32}, Na^{24}, or C^{14} means the amount of the isotope necessary to provide disintegrations at the rate of 3.7×10^7 atoms per second. Failure to distinguish between total ionizing events and total disintegrations in the case of isotopes that do not have simple decay schemes has led to confusion and error in the use of the curie. For example, with a radioisotope that emits both a beta ray and a gamma ray in each disintegration, if there are internal conversion electrons, measurement of the beta particles will lead to a too-high disintegration rate. If only the gammas are measured, a too-low disintegration rate results. Unless the number of gammas leading to conversion electrons is known, the disintegration rate will not be correct and the amount of the radioactive isotopes expressed in curies will be incorrect.

Likewise, consider the error which could arise in measuring the activity of Mn^{52}, which has a half-life of 6.5 days and decays by positron emission in 35 percent of the transitions and by electron capture in 65 percent of the transitions. One millicurie of Mn^{52} emits only $0.35 \times 3.7 \times 10^7$ or 1.3×10^7 positrons per second, even though there are 3.7×10^7 disintegrations per second.

The use of the curie to describe any radioactive source which produces the same gamma ray response as 1 curie of radon is another serious misuse of the curie unit. The objection is that the gamma ray response depends on the detection instrument used. For example, the ratio of the apparent gamma ray intensity of a source of 8-day I^{131} to a source of radon is four times as great if measured with a platinum cathode counter as when measured with a copper cathode counter. The curie should be used strictly to mean that quantity of radioactive material which has 3.7×10^{10} atoms disintegrating per second.

Rutherford

Since there is a discrepancy between the number of disintegrations per second from 1 gram of radium and the number adopted by international agreement, Curtis and Condon proposed a new unit for radioactivity, the Rutherford, defined as that quantity of a radioisotope decaying at a rate of 10^6 disintegrations per second. However, this unit has not come into widespread use. The unit used to compare source strengths is the roentgen-per-hour-at-unit-distance, which we shall define after discussing the roentgen.

Dose Units

Roentgen

A unit of radiation dose should be readily reproducible and should be measurable in terms of simple physical quantities by routine instrumentation. In most cases the ultimate information desired is the biological damage produced by a given dose of radiation; hence, it would be desirable to have our unit of radiation dose proportional to the biological damage produced. However, the factors involved in radiation damage are so complex and so little known that it has not been possible to devise a unit having both these physical and biological characteristics. The physical quantity selected must be capable of being measured with reasonable accuracy and of being expressed in absolute units. Thus, the unit of dose may be either the energy absorbed from the radiation per unit mass or the ionization produced per unit of mass.

If we select as our physical quantity the energy absorbed per unit mass of tissue, we may measure the energy in ergs or multiples of ergs, i. e., joules (1 joule is 10,000,000 ergs). In recent years another energy unit has come into widespread use because of its convenience, the electron volt, which is defined as the energy an electron acquires in falling through a potential difference of 1 volt. Frequently used is the unit Mev, which is 1 million electron volts, or that energy which an electron would acquire in falling through a potential difference of 10^6 volts. Today, particles with energies of many Mev are commonplace. Since both ergs and electron volts measure the same quantity, they must be numerically related, and therefore, we find that 1.6×10^{-12} ergs is equivalent to 1 electron volt (e. v.) or 6.2×10^{11} e. v. = 1 erg.

If our unit of dose is the ionization per unit mass produced by the radiation, we would measure it in terms of the number of charges formed per unit mass. The unit of charge we shall use is the electrostatic unit. Whichever unit of

dose is employed, energy absorbed per unit mass or ionization per unit mass, the ionization produced per unit volume is the physical quantity actually measured.

The roentgen is that "quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 esu [electrostatic unit] of quantity of electricity of either sign (*2*)." The quantity of air referred to is 1 cc. of dry air at 0° C. and 760 mm. Hg. The roentgen (r.) is a unit of radiation exposure and is based on the effect of X or gamma radiation on the air through which it passes and applies only to X or gamma radiation in air. The unit considers the ionization caused by the secondary particles (electrons) ejected from some known volume of air (1 cc. at standard conditions). The ionized tracks of these particles may go outside of the known volume, but it is important that their total ionization be collected wherever it occurs.

The roentgen is not a radiation unit. It does not describe the number of photons in the beam nor their energy; it merely gives the effect of that radiation in 1 cc. of air. Part of the energy of the radiation is given to the air in producing photoelectrons, Compton electrons or in pair production, and these secondary particles in turn produce other electrons and positive ions. When all ions of either sign are counted and are found to be 1 esu, then 1 roentgen of X or gamma radiation has been absorbed by the original volume of air. Since the charge on 1 electron is 4.8×10^{-10} esu (electrostatic units), the 1 esu of charge represents $\frac{1}{4.8\times10^{-10}}$ or 2.083×10^{9} electrons. This is also the number of ion pairs per esu, since only one partner of the ion pair is measured. Thus, the roentgen may be defined as that quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, 2.083×10^{9} ion pairs, or 1.61×10^{12} ion pairs per gm. of air. Since the energy required to form an ion pair in air is 32.5 e. v., the roentgen represents energy absorption of 6.77×10^{4} Mev/cc. of air, or 5.24×10^{7} Mev per gm. of air, or 5.24×10^{13} e. v.$\times1.60\times10^{-12}$ ergs/e. v.$=83.8$ ergs/gm. of air.

Thus 1 roentgen of X or gamma rays is that quantity of radiation in which approximately 83.8 ergs are absorbed per gram of air. Thus, according to the official 1937 definition, a dose of 1 roentgen received at any point means:

1 esu of ion pairs produced per cc. of air.
2.083×10^{9} ion pairs produced per cc. of air.
1.61×10^{12} ion pairs produced per gm. of air.
6.77×10^{4} Mev absorbed per cc. of air.
5.24×10^{7} Mev absorbed per gm. of air.
83.8 ergs absorbed per gm. of air.

One roentgen of X or gamma rays is that quantity of radiation whereby 83.8 ergs are absorbed per gram of air, but in substances of different atomic number and different density the amount of energy absorbed per unit volume for the same quantity of radiation will be different. In soft tissue the energy absorbed per gram of tissue per roentgen is approximately 93 ergs, while in bone it may be higher. Although the relative amounts of energy absorbed in different substances show wide variation, the dose is still 1 roentgen if the same quantity of radiation produces 1 esu of charge of either sign per 0.001293 gram of air at the point under consideration. The dose expressed in roentgens is totally independent of the absorbing medium exposed to the radiation and of the amount of energy that the particular medium absorbs. Nor does the roentgen depend on the time required for the production of the ionization; as long as 1 esu of charge of either sign is produced in 1 cc. of standard air, the dose delivered is 1 roentgen regardless of whether it took 1 second or 1 hour to produce the 1 esu. Consequently, dosage rates are given in roentgens per hour. For example, if a constant dosage rate of 2 roentgens per hour is continued for 5 hours, the total dose delivered is 10 roentgens, and in the 1 cc. of standard air 10 esu of charge is produced.

Since the definition of the roentgen requires that the total ionization produced by the secondary electrons formed per cubic centimeter of standard air be measured, and as some of the secondary electrons may have ranges of several meters, large and cumbersome apparatus would be needed. To avoid such large unwieldy apparatus, "air wall" roentgen chambers or "thimble chambers" have been developed. Their use is based on the principle that, when a tiny cavity such as a small ionization chamber is placed in a large homogeneous absorbing medium which is

uniformly irradiated, the atmosphere of secondary electrons in the cavity is identical in every respect with the electron atmosphere which existed in the medium before the cavity was introduced. If the chamber gas is air, and if the walls are composed of materials having an atomic number near that of air, the ionization per gram of air in the chamber will be substantially the same as the gamma-ray energy loss per gram of air at the point where the chamber is located.

Roentgen-Equivalent-Physical

The roentgen applies only to X-ray and gamma radiation; however, ionization in tissue is often produced by radiations other than photons, that is, by betas, alphas, neutrons, and protons. Thus, there is need for a dose unit applicable to corpuscular radiation, which will be a measure of the energy absorbed in tissue exposed to these radiations. The roentgen-equivalent-physical (rep), introduced by H. M. Parker, is defined as that dose of any ionizing radiation which produces energy absorption of 83 ergs per gram of tissue. Thus, if the energy loss by ionization in the tissue is the same as the energy loss for 1 roentgen of gamma radiation absorbed in air, the dose is referred to as 1 rep. The name implies physical equivalence with the roentgen, but in general such equivalence does not exist, for the rep is not equal to the energy absorbed per gram of tissue exposed to 1 roentgen. The energy absorbed in tissue exposed to gamma radiation depends on atomic composition and density of the tissue as well as on the energy of the photons, whereas a rep is always 83 ergs per gram of tissue independent of kind of tissue or the energy and type of the corpuscular radiation. In soft tissue, a dose of 1 roentgen corresponds to the absorption of approximately 93 ergs per gram. There has been considerable discussion in favor of changing the rep to 93 ergs per gram of tissue, and some persons prefer the use of 95 or 100 ergs per gram.

Roentgen-Equivalent-Man

The biological evidence indicates that the effects of the various ionizing radiations are not the same and that a different degree of tissue damage can be expected from the absorption of 100 ergs of alpha-ray energy than from 100 ergs of beta-ray energy or from 100 ergs of neutron energy. The roentgen-equivalent-man (rem) is that dose of any ionizing radiation which, delivered to man, is biologically equivalent to the dose of 1 roentgen of X or gamma radiation. The rem is not a measure of energy absorption or of ionization produced in tissue, but is rather a measure of a quantity of radiation that produces certain observed biological effects. Extensive experimental studies have been made of the relative biological effectiveness (RBE) of the ionization produced in tissue by the various types of ionizing radiations and an equal amount of tissue ionization due to gamma rays. The values obtained for the various radiations show rather wide variations with effects (blood counts, median lethal dose) and with different species of mammals. Present accepted RBE values are:

Beta rays	1
Protons	10
Alpha rays	20
Fast neutrons	10
Thermal neutrons	5

In terms of energy, 1 rem$=\frac{95}{\text{RBE}}$ ergs/gm. tissue or, in terms of the rep, 1 rem$=\frac{\text{rep}}{\text{RBE}}$. Thus, for alphas, 1 rem$=\frac{95}{20}$ergs/gm. tissue; 1 rem$=\frac{1}{20}$ rep$=0.05$ rep.

The maximum permissible tissue dose for X-rays and gammas is 0.3 rep per week, while for alphas it is 0.015 rep per week, and for fast neutrons, 0.03 rep per week; or, expressed in rem per week, for X and gammas 0.3 rem per week, for alphas 0.3 rem per week, for neutrons 0.3 rem per week. Since a rem of alphas produces the same biological damage as a rem of gammas or a rem of neutrons, doses expressed in rems are additive. Thus, an exposure to 100 millirem (mrem) of gammas and 200 mrem of neutrons is a total dose of 300 mrems.

Roentgen-Per-Hour-at-One Meter

Having defined the roentgen, we can now discuss the unit of radioactive source strength, the roentgen-per-hour-at-unit-distance. For a

particular radioactive substance which emits gamma rays, this unit provides a means of stating the amount of that substance without knowledge of its disintegration scheme. The roentgen-per-hour-at-one-meter (rhm) is that amount of a radioactive isotope whose unshielded gamma-ray emission produces 1 roentgen per hour in air at a distance 1 meter from the source. By use of a standard instrument reading in roentgens per hour, a standard technique, and the rhm, the source strength of various gamma-ray emitters can be compared and expressed in terms of the number of roentgens per unit of time, produced at some arbitrary distance. The unit has the advantage in that the disintegration scheme need not be known, whereas it must be known in order to express quantity of radioactive material in curies.

These then are the units used to express quantities of radioactive materials, the curie and the rhm; to express dose, the roentgen, the rep, and the rem. With these units it is possible to correlate the effects of radiation on living tissue with external measurements of the exposure, or with calculated internal doses.

REFERENCES

(1) Condon, E. U., and Curtiss, L. F.: New units for measurement of radioactivity. Physical Rev. 69: 672–673 (1946).

(2) U. S. Department of Commerce, National Bureau of Standards: Medical X-ray protection up to two-million volts. Handbook 41, March 30, 1949, p. 1.

Field Training Courses in Insect and Rodent Control

Field training courses in insect and rodent control will be offered during the months of March and April 1952 by the Public Health Service Communicable Disease Center, Atlanta, Ga.

The course in rodent control is scheduled for the period from March 17 to April 4. It is designed to give public health personnel a practical working knowledge of the control of domestic rodents and rodent-borne diseases. Field work, giving the trainee an opportunity to practice the principles developed in classroom lectures and discussions, will be emphasized.

A 2-week course in insect control will be held April 7–18. It will offer practical field training in the control of insects affecting the health and well-being of man. Emphasis will be placed upon the identification, biology, and control of flies, mosquitoes, and household and restaurant insects. Survey and control techniques will be demonstrated, and field practice in Atlanta and surrounding areas will be offered.

These courses are available to interested personnel from State and local health departments and the Public Health Service. Persons from other organizations concerned with insect and rodent control will also be accepted if facilities permit.

Applications should be made by letter through the sponsoring agency to: Officer in Charge, Communicable Disease Center, Public Health Service, 50 Seventh Street, NE., Atlanta 5, Ga. Attention: Chief, Training Branch.