Title
SOME CONSIDERATIONS ON THE UNITS USED IN RADIATION PROTECTION DOSIMETRY

Authors
Rindi, A.
Thomas, R.H.

Publication Date
1972-10-01

Published (in Italian) in
Giornale di Fisica Sanitaria
e Protezione Contro Le Radiazioni
16 No. 4, 177-183 (Oct.-Dec. 1972)

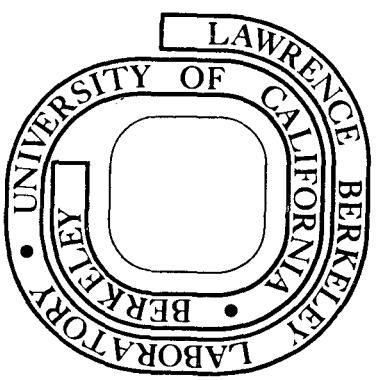
LBL-2481

SOME CONSIDERATIONS ON THE UNITS USED IN RADIATION PROTECTION DOSIMETRY

A. Rindi and R. H. Thomas

October 1972

Prepared for the U.S. Atomic Energy Commission
under Contract W-7405-ENG-48



LBL-2481

DISCLAIMER

LBL-2481

Some Considerations on the Units Used In Radiation Protection Dosimetry*†

A. Rindi and R. H. Thomas

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

*Work done under the auspices of the U.S. Atomic Energy Commission.

† A free translation of "Considerazioni sulle unita dosimetriche" from the Giornale Di Fisica Sanitaria E Protezione Contro Le Radiazioni by M. C. Rindi.

Some Considerations on the Units Used In Radiation Protection Dosimetry

Introduction

The International Commissions on Radiological Protection and Radiation Units and Measurements (the ICRP and ICRU) are under attack. For years the authority of these institutions in the fields of dosimetry and health physics has been unchallenged: it is now being disputed on two sides.

On one side the attack is mounted by a polyglot assortment of people drawn from various disciplines and spurred on with the zeal of "fighting pollution" - a problem to which society on both sides of the Atlantic has only recently become aware. Some of these zealots have demanded reductions in exposure limits. They have done this, not in the usual scientific forum, but in the glare of the mass news media. These critics of the "radiation protection establishment" have chosen to fight their battle with pseudoscientific weapons. They complain of what they claim to be the lack of foresight by official organizations in setting adequate radiation protection standards. On the positive side of their campaign they seek to clearly delineate both the methods used in setting protection limits and the criteria to be used in risk benefit analysis. It is not our intention here to discuss this aspect of the struggle with the ICRP.

On the other side in this struggle are the "physicists" working in the field of health physics, the people in charge of "weighing" radiation or "quantifying" radiation fields; to use terms more scientific if not more understandable, those people who evaluate dose equivalent: the dosimetrists. For some time some of them have felt uneasy in their work because of the excessive number of quantities it is recommended they must evaluate in order to determine the dose equivalent (H), that notorious definition of "quantity of radiation" enforced by the official authorities for protection measurements.

It is seldom possible to meet all the criteria necessary for an exact determination of dose equivalent, and in consequence the health physicist is forced to evaluate measurements variously expressed in rads, rems, particles per cm^2, or measurements made with remmeters, linear-energy-transfer (LET) spectrometers or quality-factor (QF) meters to mention only a few. (Many more possibilities are mentioned in ICRU Report 19.)[1] While it may be true

that all these different techniques and radiation units are of value -- and who are we to deny it? -- it is also true that they cause an incredible confusion in the interpretation of routine survey measurements which is one of the tasks of the health physicist.

The dosimetry of simple radiation fields, composed of beta particles or gamma rays of energy up to a few MeV, is relatively simple. The exposure (in roentgen), the absorbed dose (in rads), and the dose equivalent (in rem) are approximately numerically equal. In such cases the QF is unity and there is no need to determine the LET distribution of the radiation field; relatively simple instruments suffice for measurement.

Dosimetry becomes more difficult in neutron fields, even at the relatively low energies found around nuclear reactors. In these fields the QF of the radiation is greater than unity; a measurement of air exposure (in roentgen) is inappropriate, and a measurement of the absorbed dose (D) with a tissue-equivalent chamber is not sufficient to determine the dose equivalent. Dosimetry in these radiation fields is already in "unorthodox" routine practice. Very few health physicists measuring the radiation environments around nuclear reactors evaluate H from the classical equation that defines it[1]:

$$H = DQN \qquad (1)$$

where D is the absorbed dose, Q is the Quality Factor, and N is the product of any other modifying factors.

Typical neutron spectra around reactors have been measured (generally for purposes other than radiation protection) and the techniques of measurement have been perfected so that one fluence measurement at two or three points in the spectrum is often sufficient to quantify the spectrum itself and permits an evaluation of the dose equivalent with an accuracy adequate for radiation protection. The gamma component can be measured by a determination of exposure. However, since our knowledge of neutron fields around reactors is quite detailed, it is also possible to evaluate the dose equivalent by the "orthodox" techniques of absorbed-dose and LET-distribution measurement.

The problem becomes more complex at high-energy accelerators. Here we are confronted with radiation fields consisting of many particles:

protons, electrons, heavy ions, muons, and neutrons whose energies vary between thermal and the primary-beam energy. An evaluation of the dose equivalent by orthodox techniques, is at best, extremely difficult, and in our opinion, impossible, unless much detailed information concerning the composition of the radiation field is available: the type of particles, their energies and fluences. However, when this information is known, the corresponding dose equivalent may be calculated precisely, preempting the need for a measurement of absorbed dose and determination of the LET distribution.

Later, we will discuss the historical origins of the dosimetric units in current use. These units will then be individually analyzed, and finally, a method of expressing the dose equivalent due to exposure to radiation environments will be discussed.

The Origins of Today's Dosimetric Units

If we retrace the evolution of the present dosimetric units, our impression is that the present situation derives from attempts to define radiation units that measure biological effects rather than some physical effects of the radiation field.

The birth of dosimetry is contemporaneous with the discovery of x-rays in 1895. Skin erythema, which was one of the first biological effects of radiations that was observed, was causally linked to radiation exposure. Attempts immediately followed to quantify radiation exposure.

Roentgen himself observed many of the physical effects produced by x-rays -- which are still today used to measure radiation exposure -- such as blackening of photographic film, color changes in certain chemicals, and the ionization of air. This last effect was chosen as a standard means of quantifying radiation, laying the foundation for the unit of exposure: the roentgen (later restricted to x- and γ-rays below 3 MeV). The roentgen is that quantity of radiation that produces in one cubic centimeter of standard air, ions carrying one electrostatic unit of charge. From this definition the roentgen appears clearly to be a unit of exposure, a unit measuring the radiation field through a physical and easily detectable effect. It is significant that in the minds of these pioneers the biological effects due to ionizing radiation were related to the radiation quantity incident on the body: the exposure.

This simple viewpoint survived only as long as radiation effects at the surface of the body were considered, i.e., for low energy x-rays. With the development of higher energy x-ray tubes and the discovery of naturally radioactive elements and their more penetrating radiations, this direct relation between exposure and biological effect was no longer valid. Therefore, in addition to the exposure (in roentgens), information indicating the penetrating power of the radiation -- such as x-ray tube voltage, x-ray tube filtration or radioactive element -- were provided. Nevertheless radiation exposures were conceptually related to the quantity and type of incident radiation rather than energy absorption in the irradiated tissue.

As a result of fundamental change in the thinking of radiobiologists, the 1930's brought about a fundamental change in the basis of dosimetry. At that time the view that the effects of radiation were related to the macroscopic deposition of energy in the body or organ irradiated was widespread amongst radiobiologists. Consequently the underlying basis for dosimetric measurement changed from the concept of exposure to that of energy deposited in the body, regardless of the type of the radiation. After a long period of maturation, the rad was officially adopted in 1953. The introduction of this unit ended the attempts to measure the neutron exposure in roentgens. It is interesting to note, however, that the exposure concept, although restricted to x rays and gamma measurements remained in all ICRU publications, and that even today many radiobiologists continue to use it as the basis for their measurements.

Had it been possible to prove that biological effects were directly related to the absorbed dose in the organ being studied, success for the concept of absorbed dose would have been certain.' It soon became apparent that equivalent absorbed doses had different biological effects, depending on the type and energy of radiation, and the organ being considered.

At this stage the concept of relative biological efficiency (RBE) was introduced as that quantity that allowed one to evaluate the "biological quality" of radiation relative to a radiation standard (eg. x-rays produced by a 250-kV machine). Then the RBE of different types of radiations for different biological effects were measured.

The Manhattan project and the development of nuclear energy stimulated the various studies for radiation protection. The need to protect workers

from exposure to different types of radiation demanded that the exposures to different types of radiation be summed, and caused the introduction of the RBE dose. The RBE dose is the product of the absorbed dose in rads and an RBE value selected for the particular radiation. In addition to the absorbed dose measurement, usually performed using an ionization chamber with tissue-equivalent walls and gas filling, the type of radiation had to be known in order to select the appropriate RBE. The tissue equivalent chamber to be used was not precisely specified and since the measured absorbed dose strongly depends upon chamber wall thickness and volume, substantial variations in measured values were possible.

As knowledge of biological effects of radiation increased, it became clear that the RBE was related to LET. The LET was in turn considered to be a physical parameter which identified the radiation quality by virtue of its biological effects. It should be borne in mind, however, that no unique relation between LET and RBE has yet been established. The importance of the microscopic distribution of energy depositions became increasingly apparent. Radiation does not deposit its energy uniformly along its path, and a measurement of the average deposited energy is insufficient to predict its effects.

Nevertheless, it was considered useful for protection purposes to divide the RBE into several components; the name of 'quality factor" was given to that part of the RBE dependent on the LET of the radiation, and the relationship between the QF to the LET was defined.

Finally the dose-equivalent (H) was defined for radiation protection purposes and expressed by the relation given in Eq. (1). The practical aspects of the equation will be discussed in the next section. It should be borne in mind that the "other modifying factors" of Eq. (1) are not defined and set equal to unity at the present time.

Is an Orthodox Measurement of Dose Equivalent Possible?

It is unfortunate that ICRP recommendations are often misunderstood. If one carefully reads ICRP Publication 15[2] he will find it clearly stated in the section discussing quantities and units that dose equivalent cannot be measured. Paragraph (15) reads specifically ..."neither the absorbed dose nor the dose equivalent can be measured directly in any of the critical organs. Thus, to

obtain the dose equivalent in any position within the body, one must make measurements of the radiation fields outside the body...."

Nonetheless, many dosimetrists are lured by the apparent simplicity of the expression

$$H = D\,Q \qquad (1a)$$

(For simplicity's sake the other modifying factors in the expression are omitted.) Equation (1a) defines dose equivalent only in a qualitative way.

A better quantitative definition of dose equivalent is

$$H = \int_0^{L_{max}} D(L)\, Q(L) dL, \qquad (2)$$

where L is the LET of the radiation under study, D(L) is the absorbed dose in the point of interest for unit interval of L at L, Q(L) is the value of Q for this L (given by the doubtful relations established by the ICRP) and L_{max} is the maximum value of L at the point of interest.

Of course, Eq. (2) requires the point of interest to be known. This point is usually one of the critical organs of the human body. To define the location of the point of interest one must know the type of radiation and the spectrum. If an LET spectrometer is available it can be used to make measurements behind increasing depths of tissue-equivalent material until the maximum value of H is located.

Equations of the form of (1) and (2) have tantalized dosimetrists into attempting to build instruments capable of measuring the dose equivalent. Some general comments on these instruments are:

a) No instrument developed to evaluate DE can function correctly if the physical characteristics of the radiation field (type of radiation, energy spectrum) are inappropriate to the design of the instrument.

b) Rem meters do not, in general, attempt to measure the quantities specified in Eqs.(1) and (2).

c) Some of these instruments may not be used in routine protection measures: their sensitivity is usually too low. For example, recombination chambers require very intense fields, and Rossi's proportional counters, though usable in low intensities, require very long measuring times. There are other problems in the use of these instruments; for example, the

recombination ionization chamber depends upon the principle that the relationship between the collected current and the applied voltage gives an index proportional to the average LET of the radiation. This is only true under conditions of columnar recombination. These devices, therefore may not be used for any type of radiation and are, at most, able to indicate only an average LET or an average QF; nor can they make surface or soft-radiation measurements.

Other more complex instruments, like Rossi's spherical counter, also have difficulties; nonetheless they have provided the fairly reliable LET spectra that may be compared with those obtained by calculations based on the knowledge of the energy spectrum of the incoming radiation.

How Can Dose Equivalent be Evaluated?

The question arises - independently of the technical limitations of instruments designed to measure absorbed dose and LET spectra: Are these the measurements of choice for protection purposes?

The measurement to be made for protection purposes, besides indicating the dose equivalent in a given radiation field, should also provide the necessary data by which the field may be modified. For example, shielding calculations require details of the type of radiation to be attenuated, its intensity and energy spectrum. These parameters may also be used to calculate dose equivalent.

Measurements of neutron spectra and fluence in radiation fields such as are found around particle accelerators or reactors are far from simple. In theory, using complex instruments of the kind used in experimental particle physics, one could make precise measurements of differential spectra. But using such instruments for protection measurements is not feasible. Nonetheless, the practical techniques developed to date provide field measurements precise enough for calculating shielding, and for evaluating the dose equivalent even though, for some fields, improvement is needed.

Why then waste our efforts inventing instruments for protection determinations that will evaluate the DE "more directly" by Eqs. (1) or (2)? Measurements of LET spectra and of microscopic energy distribution are of interest in radiobiology, but the needs of radiation protection are distinct

enough to warrant separate consideration. These considerations of ours may seem obvious if one examines closely the manner in which protection measurements around accelerators and reactors are performed.

In a 1966 report[4], D. Nachtigall showed that, of seven research laboratories surveyed as to routine measurements, all use instruments which determine fluence in different energy intervals; some laboratories also used, in addition, a tissue-equivalent ionization chamber. We don't believe the situation around reactors is very different.

Neutron rem meters of the Andersson type are nothing but instruments measuring the neutron flux density with a spectral sensitivity carefully elaborated to match the dose equivalent-flux relationship. Unfortunately, even if these instruments do make the operational health physicists' job easier by allowing a direct reading in rem, they have the disadvantage that no details of energy spectrum are observed. Nevertheless, many people still feel that the measurement of particle fluence to evaluate dose equivalent is merely a last resort to be used only in the absence of better techniques. Such people live in the constant hope that perhaps someday someone will invent an "instrument for measuring the DE." To some extent, as we said before, this attitude is encouraged by the recommendation of the ICRP and ICRU which persist in presenting the fundamental definition of dose equivalent in the form of Eq. (1).

Increasing public concern for radiation exposure may necessitate the measurement of dose equivalent rates as low as a few millirem/yr. This would represent a formidable challenge to operational health physicists, and so we judge it useful to review the practical formulation of the measuring units. We think the following propositions should be taken into consideration:

a) Dose equivalent must be redefined in a more rational and practical form. It is better defined as the product of a measurable physical quantity (A) by a coefficient relating the physical measurement to the chosen biological effect more consistent with the overall risk (B) and by an administrative factor (C) that would take account of the uncertainties in the relation between the physical quantity and the biological effect: The general expression for DE would then be:

$$H = (A) \times (B) \times (C) \qquad (3)$$

In our opinion, the most appropriate quantity for (A) is the particle energy spectrum measured in selected energy regions as discussed above.

b) The quantity (B) is then the flux-to-dose conversion factor, calculated for selected energy ranges and for standardized exposure conditions[5].

c) The quantity (C) that we have called an administrative factor will have to include the uncertainties of low dose extrapolation, dose-rate effects, and geometrical factors. This could be periodically revised when progress in scientific knowledge should require it.

REFERENCES

1. International Commission on Radiological Units (ICRU) Report 19 (1971)
2. International Commission on Radiological Protection (ICRP) Publication 15 (1969).
3. Ibid., ref. (2), § 13.
4. D. Nachtigall "Difficulties encountered in high-energy radiation dosimetry" CERN Internal Report ISR - BT/66-19 (1966).
5. International Commission on Radiological Protection (ICRP) Publication 21 (1973).

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720