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DISCLAIMER

"POVERA E NUDA VAI, DOSIMETRIA"*

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Abstract - The concepts used in radiation protection are critically reviewed. It is concluded that primary attention should be given to the specification of radiation fields in terms of particle flux density and energy spectra, from which all other parameters needed in health physics may be derived.

* A corruption of a quotation from "Le Rime Sparse" of F. Petrarca in which he laments the sad condition of philosophy. "You are cold and hungry, oh philosophy," he says (Povera e nuda vai, Filosofia). The authors have similar views of the present condition of dosimetry in radiation protection.

1. INTRODUCTION

A major objective of the health physicist is defined by ICRP: "To prevent acute radiation effects and to limit the risks of late effects to an acceptable level."[1] In performing this task the operational health physicist is called on to quantify radiation fields (or radiation exposures) by a variety of physical techniques and relate his measurements to some given radiation safety standards.

In making recommendations of maximum permissible doses one must recognize their two distinct facets. On the one hand is the problem of the physical quantification of the radiation fields, on the other is the expression of these physical measurements in terms of statistical probability of radiation injury. Although our ability to quantify radiation fields in physical terms could be relatively accurate, at least for external radiation exposures, our knowledge of radiation effects at low doses and dose rates in man unfortunately do not permit the second step to be made with great accuracy. (We use the terms "precision" and "accuracy" in their statistical senses:[2] accuracy of an experiment is a measure of how close the result of the experiment comes to the true value (or its best estimate from statistics); precision of an experiment expresses how exactly the result is determined without reference to what that result means: it is a measure of how reproducible the result is.)

Recognition of inaccuracy in our estimates of risk has led to some reluctance to prescribe in great detail the technique for translating physical measurements to dose equivalent.

In its definition of dose equivalent the ICRU speaks of the "immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection."[3] This scale cannot be specified with great accuracy, because this would demand a good understanding of radiation effects at the doses and dose rates within the limits of radiation protection. At present it must be somewhat arbitrary, and only loosely related to biological effects. It need not, nevertheless, be vague and imprecise. The ultimate aim of definitions and prescriptions in dosimetry for radiation protection must be to permit the translation of high-accuracy physical measurements to precise estimates of dose equivalent. Because the prescription for dose equivalent is an agreed administrative procedure, this precision is determined only by the accuracy of the physical measurements. These procedures must be given in sufficient detail that the precision of the estimated dose equivalent reflects the accuracy of the original physical measurement, as far as possible.

Before specifying a numerical scale for radiation protection, it is imperative that it be decided with what precision measurements on the scale be reproduced. There are wide differences of opinion among health physicists on just what this precision should be. On the one hand, we have those who suggest measurements of annual dose equivalent rates be made to an accuracy of a few percent (even at the level of natural background), while on the other, we have those who suggest, it seems to us, that inaccuracies of as much as a factor of five or more are tolerable at the maximum permissible dose (MPD).

The ICRP has recommended that "the uncertainty in assuming the upper limits to the annual dose equivalent to the whole body or to the organs of the body"... should not exceed 50%.[4] Members of an ICRP panel at the IRPA Congress held in Brighton, England in 1970 suggested that the DE resulting from external whole-body radiation exposure, at about the level of MPD should be established with a precision of about 20 to 30%.[5,6]

Many factors bear upon the precision that is required of measurements expressed on our numerical scale. There is a need to compare data between different laboratories taken under different conditions and at different times. Such comparisons are meaningless if the precision of the data is poor. In many countries radiation exposure safety standards are specified in law and it is doubtful if large uncertainties in the estimation of radiation exposures at the level of the MPD are envisaged. Finally, accurate measurements of radiation environments assure efficient and economic operation.

It would be absurd to demand precision requiring extraordinarily difficult measures, but, conversely, equally absurd to throw away precision that is easily attainable. The precision which can be demanded is, in general, not limited by the techniques used to determine the physical characteristics of radiation environments. When different techniques of physical measurements are used the limitations on precision are likely to be determined by the care which the administrative procedures for conversion to DE have been specified.

In what follows we assume that a precision of about 25% is desired in estimates of external whole-body exposure to radiation at the level

of the MPD.

When translation of the physical measurement into dose equivalent is unambiguously agreed, then the operational health physicist can give his undivided attention to making accurate physical measurements. We have suggested that good accuracy in physical measurements is achievable, at least for external radiation fields, at the present state of the art in radiation detection. This holds true, however, only when the quantities to be measured are clearly defined. The physical quantities to be determined in the radiation field must be defined: in a rational way, so as to have meaning to the physicist asked to measure them; in a simple but unambiguous way, to allow the required and obtainable accuracy; and in a standard way, to allow intercomparison of the results. The historical development of radiation has led to a certain confusion between attempts to explain the biological effects of radiation (which is mainly the goal of the radiobiology) and to quantify radiation fields and interpret them on a scale of risk (which is the aim of health physics). In consequence, concepts and quantities that have been of paramount importance along the difficult way of understanding the mechanism of biological damage have been inappropriately introduced in health physics. We believe that nowadays health physics deserves to be considered as a distinct branch of science, related to radiobiology as well as to physics and chemistry.

Over the past few years several authors have critically reviewed the recommendations of the ICRP, from the points of view of both interpretation and implementation. [6-20] They all express an uneasiness in the application of these recommendations to operational

health physics -- an uneasiness reflected, to some extent, by the ICRP itself.[21]

In view of this uneasiness we briefly review the evolution of our present radiation-protection units and critically examine their present application, and the offer some proposals that, in our judgment, would lead to both conceptual and practical improvements.

HISTORICAL REVIEW OF DOSIMETRY IN RADIATION PROTECTION

In the autumn of 1895 Health Physics was in fact born, although it was to take several years before the subject achieved the status of a separate and distinguishable branch of science. Roentgen, in studying the conduction of electricity through rarefied gases, noticed that a barium platinocyanide screen placed close to a discharge tube glowed with a brilliant light. In his first report of his discovery[22] of what he called "x rays," he noted that these emanations had the property of discharging electrified bodies — a penetrating observation which was to be of great significance in the dosimetry of ionizing radiations.

The practical application of Roentgen's fortuitous discovery was taken up with amazing rapidity. Thus, for example, within 3 months x rays were being used to assist surgery in hospital.[23] Neither did it take long to discover the deleterious biological effects of x rays; the need for protection from their effects became obvious all too soon. Within months of their discovery reports of skin erythemas and other more severe manifestations of radiation injury had appeared in the literature.[24] Many excellent reviews[25-27] of man's early experiences

with the use of ionizing radiation show how rapidly the early pioneers realized the need to quantify exposure to ionizing radiation and relate it to biological damage.

It was soon discovered that x radiation could be readily quantified by several physical techniques, viz., the blackening of photographic film, the ionization of air, and the discoloration of certain chemicals.[28]

Of the physical techniques available for the quantification of x rays, their production of ionization in gases proved to be the most reliable and convenient -- a circumstance confirmed by the adoption of the roentgen as the unit of radiation exposure by the ICRU in 1928.[29]

Roesch[30] has pointed out a lack of unanimity as to the precise meaning of the definition of the terms "exposure" and the "unit roentgen," as is evidenced by the subsequent evolution of the concepts in ICRU publications of 1938,[31] 1957,[32] and 1962.[33] It seems clear, however, that foremost in the minds of the early pioneers of radiation protection was the idea that biological effects were quantitatively related to the "amount of radiation" (now called exposure) incident upon the irradiated person.

In this regard it is of interest to note that one of the earliest radiation-protection standards directly related biological effects to the roentgen. Mutscheller[34] proposed a maximum annual permissible limit to exposure from x rays of one tenth of an erythema dose, corresponding to 25 to 50 R per year, depending upon the voltage of the x ray tube used. Characterization of a field of x rays incident on the body by a measurement of ionization in air was believed

sufficient to predict biological effects.

The desirable simplicity of this view was due in part to the rather low voltage ranges of the x rays then available to the early radiologists. As the energy of the x-ray sources increased and the radiations emitted by radioactive substances discovered by Becquerel (at about the same time that Roentgen first observed x rays) had been investigated it soon became clear that a simple measurement of ionization in gas alone was insufficient; and it became common practice to specify, in addition to exposure, information related to photon spectrum, such as the voltage of the x-ray tube or the filtration used.

This additional information then permitted better prediction of biological effects, and to this day such a technique is used in radiotherapy,[35] where the distribution of energy absorption in patients exposed to x rays is calculated from a measurement of exposure and knowledge of the incident photon spectrum.

Time was not yet ripe for the detailed application to photon fields of the fundamental concepts of particle fluence, flux density, and energy spectra -- familiar from the kinetic theory of gases -- because theories of the dual corpuscular and wave nature of photons were still evolving. Nevertheless the concepts of exposure and fluence are philosophically rather close. They both attempt to define the radiation field independently of its interaction with tissue.

In the late thirties and forties it increasingly became the opinion of radiobiologists that the quantity of energy absorbed by biological systems was a better measure of their biological response than exposure. Moreover, severe difficulties were met in measuring

exposure doses of neutrons by ionization in air. However, the first approaches to evaluation of absorbed energy were made through the measurement of exposure. We quote from D. E. Lea: [36]

"The roentgen is a unit of dose internationally accepted for γ rays and x rays, and capable of obvious extension to cover most of the other ionizing radiations. It is a unit chosen primarily for convenience in physical measurement, and while 1 R of any radiation represents the same amount of ionization in air it does not always represent the same ionization or energy deposition in tissue. It is necessary therefore in comparing the efficiencies of different radiation to be able to convert roentgens into ionization in tissue or into energy dissipation in tissue. There is no difficulty in principle in converting roentgens into energy dissipation in tissue, and if the elementary analysis of the tissue is known the conversion can probably be made with an error of less than 10%.

"The most obvious unit of energy to employ is the erg. One R of γ rays or x rays involves the dissipation of about 90 ergs/g of tissue."

Contrary to Lea's opinion, however, attempts to extend the use of the roentgen to the measurement of neutrons through the "n unit" [37] in the United States or the "v unit" [38] in the United Kingdom proved abortive. Conceptually, the idea of energy absorption represents a radical departure from the earlier idea of relating biological effects directly to the external radiation field in which the body is irradiated. It stands or falls on the simple test of whether or not biological responses are closely related to energy absorption.

Unfortunately, equal absorbed doses may not always give rise to

equal probabilities of any given biological effects,[39] i.e., equal amounts of energy deposited by different radiations produce different "amounts" of the biological effect.

In an attempt to overcome these difficulties two other concepts, those of relative biological effectiveness (RBE) and of RBE dose, were introduced.[40] The absorbed dose of the radiation was transformed into a "biologically equivalent" absorbed dose of standard radiation called the RBE dose by application of an empirically determined RBE. Thus the biological effects of irradiation by n different types of radiation would be identical to that from

$$\sum_{i=1}^{i=n} (\mathrm{RBE})_i D_i \text{ rads of standard radiation,}$$

$$(\mathrm{RBE})_i = D_x/D_i,$$

and D_x, D_i are the absorbed doses of standard radiation and ith radiation required to produce the same biological effects.

It is, however, interesting to remark that the original unit of RBE dose — the rem — symbolized the phrase "roentgen equivalent man," showing how closely it was linked to measurement of exposure; at this time (circa 1950) RBE was determined from measurements of exposure rather than from absorbed dose.

There are many RBE's, even for a given type of radiation depending upon dose rate, dose distribution, biological end point, and many other biological and physical factors. In radiation protection we are often concerned with whole-body chronic low-level exposures. The biological effects of such exposure are not completely defined.

but include cancer induction, cataract formation, life-span shortening, and deleterious mutations. Unfortunately, there are no data on RBE's for these effects at sufficiently low dose rates, and the RBE's used in health physics have been extrapolated from a variety of radiobiological data.[41] The introduction of RBE, although it was intended to be helpful, served to open the door to proliferation of the quantities and terms used in radiation protection.

Radiobiologists next came to be of the opinion that one of the most important factors influencing the biological efficiency of radiation is its linear energy transfer.[42] Finally, in 1953 the ICRP/ICRU decided it would be more convenient to separate the "RBE for radiation protection" into several modifying factors. One of these, the "quality factor," is a function of linear energy transfer alone.

We cite (from Ref. 43): "In radiation protection it is necessary to provide a factor that denotes the modification of the effectiveness of a given absorbed dose by LET (linear energy transfer). Unlike RBE, which is always experimentally determined, this factor must be assigned on the basis of a number of considerations, and it is recommended that it be termed the quality factor (QF). Provisions for other factors are also made. Thus, a distribution factor, DF, may be used to express the modification of biological effect due to nonuniform distribution of internally deposited radionuclides. The product of absorbed dose and modifying factors is termed the dose equivalent, DE. As a result of discussions between ICRU and the ICRP the following formulation has been agreed upon.

The Dose Equivalent

1. For protection purposes it is useful to define a quantity which will be termed the dose equivalent (DE).
2. (DE) is defined as the product of absorbed dose, D, quality factor, (QF), absorbed dose distribution factor, (DF), and other necessary modifying factors:

$$(DE) = D(QF)(DF) \cdots \quad (1)$$

3. The unit of dose equivalent is the rem. The dose equivalent is numerically equal to the absorbed dose in rads multiplied by the appropriate modifying factors."

The dose-distribution factor (DF) takes account of the distribution of internally absorbed radionuclides and is inappropriate to external radiation. In this case dose equivalent may be written as

$$DE = D \times QF \times (M_1 \times M_3 \cdots M_i), \quad (2)$$

where the M's represent the "other necessary" modifying factors. This formulism is theoretical because in actual practice the additional factors M_1, M_2, etc. are undefined, and the dose equivalent for any type of radiation and for any external exposure condition is put numerically equal to the product of absorbed dose in rads and the quality factor:

$$DE = D \times QF. \quad (3)$$

Despite the apparent simplicity of this prescription for operational health physics, it is nevertheless extremely complex. Evaluation of the dose equivalent by direct measurements of both absorbed dose and quality factor as implied by Eq. (3) is not possible, and, as we shall show in the following sections, it is necessary to elaborate

and extend these simple definitions to administer this prescription. This extension has resulted in the definition of a host of ancillary parameters in wide use, but not authoritatively defined, and some consequent confusion.

3. CRITICAL REVIEW OF OPERATIONAL DOSIMETRY UNITS

3.1 Absorbed Dose

The concept of absorbed dose D is readily understandable: the energy per unit mass imparted to matter by ionizing radiation. ICRU report 11 defines it as "the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of the matter in that volume element,

$$D = \frac{\Delta E_D}{\Delta m} \quad " \qquad (4)$$

However, one should not be disarmed by the apparent simplicity of the definition of absorbed dose. This definition is incomplete without specification of the size of the volume element [44] but this may not be done unambiguously under all circumstances without specifying the radiation environment to be measured. The prescription that the volume element "on the one hand is so small that a further reduction in its size would not appreciably change the measured value of the quotient of energy by mass and on the other hand is still large enough to contain many interactions and be traversed by many particles" is of little practical help because it demands sufficient knowledge of the radiation field before the size of the element may be determined. Even if the size of the volume element is defined precisely there is only one instrument that allows direct absolute measurement of

absorbed energy — the calorimeter. At the dose rates experienced in health physics it is too insensitive.

Measurement of ionization in a gas provides an indirect means of absolute determination of the energy deposited in the gas. Free-air ionization chambers are limited to the measurement of photons of energy below 3 MeV, and of course, knowledge of absorbed dose in tissue is the quantity demanded by the ICRU formulism for radiation protection. Absolute indirect determination of energy absolute indirect determination of energy absorption in dense material is possible if cavity chambers operating under conditions prescribed by the Bragg-Gray principle are utilized. It has to be realized, however, that it is very difficult to obtain in practice the conditions required for the application of the Bragg-Gray principle. The composition of the walls of the chamber, the thickness of the walls, and the composition of the gas are very critical parameters and are related to the type of radiation to be measured.

Even when these technical problems are solved there are severe practical difficulties in the direct measurement of absorbed dose in the human body. Extensive development of ionization chambers whose walls and gas filling approximate the composition of tissue has been reported in the literature.[45] Such chambers have been widely used around some high energy accelerators,[46] but severe practical limitations make their use at low dose rates inconvenient in routine health physics. In unknown radiation fields, a single measurement of absorbed dose is not enough: depth-dose distributions are required for providing the information needed for a correct evaluation. The

rather large volume of adequately sensitive tissue-equivalent chambers makes depth-dose studies in phantoms difficult, with the result that measurements are often made outside the body. In such a case, of course, depth-dose distributions must be calculated from a physical knowledge of the incident radiation field.

Thus, although the concept of energy absorption in tissue represented a philosophical departure (Section 2) from the idea of quantifying the radiation field per se, in practice, no change resulted.

3.2 Relative Biological Efficiency and Quality Factor

As discussed in Section 2, the fact that equal absorbed doses of radiation do not produce equal probabilities of any given biological effect was first expressed by the definition of the relative biological efficiency (RBE), which subsequently was modified to quality factor (QF) for radiation-protection purposes.

The differences between RBE and QF are clearly expressed in ICRU report 11. RBE is always experimentally determined, and its use should be reserved for radiobiology. QF is to be used only in radiation protection and "assigned on the basis of a number of considerations," and is a "factor that denotes the modification of the effectiveness of a given absorbed dose by LET (linear energy transfer)." Unfortunately, these differences are still not clearly understood, as evidenced by numerous references in the literature to "measurements" of QF and by the undue concern often exhibited at discrepancies between measured RBE's and the recommended QF's.

ICRU report 11 has also left a vacuum in that no reference is made to high exposures. Accident dosimetry might properly be included

within the province of "Radiation Protection," but the use of "Quality Factors" is inappropriate, RBE's between 1 and 2 being generally observed for acute exposure at high doses, even for those radiations which have been assigned much higher QF's.

The introduction of the term quality factor has necessitated the further definition of linear energy transfer.

3.3. Linear Energy Transfer (LET) and QF

ICRU report 11 defines linear energy transfer or restricted linear collision stopping power (L_Δ). ICRU report 11, paragraph 19, states:

"The linear energy transfer or restricted linear collision stopping power (L_Δ) of charged particles in a medium is the quotient of dE by dl, where dl is the distance traversed by the particle and dE is the mean energy loss due to collisions with energy transfers less than some specified value Δ,

$$L_\Delta = \left(\frac{dE}{dl}\right)_\Delta \qquad (5)$$

Note that, although the definition specifies an energy cutoff and not a range cutoff, the energy losses are sometimes called energy locally imparted."

It is not yet known what value of energy cutoff should be used, and it is common practice to include all possible collisions in the calculation of LET for radiation-protection purposes. In this case, linear energy transfer is numerically identical to the stopping power of the medium. It is usually sufficiently accurate for radiation-protection purposes to calculate the stopping power in water, as has been done in definition of the QF-LET relationship.

Values of QF as a function of LET were first proposed by ICRP in 1954 and later approved by a joint ICRP/ICRU committee, the so-called "RBE Committee."[47] This QF-LET relationship has been assumed by many to be the cornerstone of dosimetry in radiation protection, but it should be clearly understood to be arbitrary and only broadly related to radiobiological data. In its first form, it was presented as a set of values over a range of stopping power in water. Later it was presented as a set of five discrete values of QF for corresponding discrete values of stopping power in water between 3.5 and 175 keV/μ. A smooth curve joining these points is used in calculation of dose-equivalent distributions.

We want to underscore here the fact, discussed more fully in paragraph 3.5, that QF is <u>not</u> a physical quantity, it has no physical dimensions and <u>cannot</u> be measured in the physical sense. The curve that relates LET and QF can, of course, stimulate the ingenuity of skilled technicians to build instruments that measure LET and thus compute the QF.

3.4. LET Distributions

Equation (3) applies to particles of identical LET. Unfortunately, even monoenergetic particles develop secondaries with a wide range of LET in tissue. In general it is therefore necessary to derive the LET spectrum developed in the region where the absorbed dose is determined. If this spectrum is known the ICRP[48] writes the dose equivalent as

$$DE = \int_0^{L_{max}} D(L)\, QF(L)\, dL, \qquad (6)$$

where L is the linear energy transfer,

D(L) is the absorbed dose at the point of interest per unit interval of L,

QF(L) is the quality factor at L,

and

L_{max} is the maximum value of linear energy transfer at the point of interest.

The effective quality factor $\langle QF \rangle$ at the point of interest is then

$$\langle QF \rangle = \int_0^{L_{max}} QF(L)D(L)dL \Big/ \int_0^{L_{max}} D(L)dL. \qquad (7)$$

(The location of the point of interest will be determined by the type of radiation and location of the various critical organs in the body. It cannot therefore be defined without specification of the radiation environment in which the body is located.)

The direct measurement of LET distributions demanded by Eq. (6) is very difficult.[49] Rossi and his colleagues have developed a spherical proportional counter for use as an LET spectrometer which has been used in several laboratories with some success.[50] The technique, however, is fairly complicated, time-consuming, and insensitive at the radiation levels usually encountered in radiation-protection work. For example, a recent survey by Freytag and Nachtigall[51] of the experimental techniques used to determine DE rate at 23 accelerator centers showed that only one had an LET spectrometer in common use and three others in occasional use. All the laboratories, on the other hand, used particle flux measurements in their routine operations.

This lack of use of LET spectrometers is easily understood, when

when one considers the extremely laborious nature of the technique, described in more detail in the paper. In general, however, LET distributions must be calculated,[49] and this, of course, demands detailed physical knowledge of the radiation field. If sufficient data is available to permit the calculation of LET distributions then dose equivalent distributions may also be calculated and Eq. (7) becomes of little practical importance.

3.5. Dose Equivalent

Dose equivalent as defined by Eq. (3) is not a simple parameter. We have seen in the foregoing paragraphs how its mechanical evaluation necessitates the definition of several additional concepts not evident from the disarming simplicity of the fundamental equation used to define it. Indeed, dose equivalent is not itself completely defined in the publications of ICRP and ICRU. One particularly important aspect left undetermined is its physical dimensions. It seems evident, however, that if the arguments of the latter part of Section 2 are accepted, then dose equivalent should be expressed in health physics as well as in radiobiology in terms of "equivalent rads of standard radiation," since the concept attempts to provide a "scale that may be used for numerical expression in radiation protection."[52]

Although dose equivalent has not been fully defined in the publications of the ICRP and ICRU, there is an increasing tendency to regard it as an expression of an upper limit to the statistical risk resulting from human exposure to ionizing radiation. At present our knowledge of fundamental radiobiology limits our ability to express this risk with precision, consequently our radiation-protection standards contain

administrative elements based on the best judgment of the ICRP and ICRU. The dose equivalent is a hybrid quantity compounded of three elements, the first consisting of physical data derived from measurements of radiation fields, or from its interaction with the tissue, the second consisting of factors derived from radiobiology, and the third consisting of administrative factors which, in view of our imprecise radiobiological knowledge, can express only general safety factors. Often the second and third element are combined into a single factor, which is of necessity somewhat arbitrary and only broadly related to biological effects. The "quality factors" recommended by the commission are examples of such a combination.

Dose equivalent is then by definition immeasurable. It must be estimated from the results of a physical measurement by rules and procedures recommended by the ICRP. It is perhaps unnecessary to remind the reader that the very useful so-called "Rem Meters" merely attempt to incorporate the task of measurement and conversion into a single operation.

Many acceptable physical techniques have been developed for the quantification of radiation fields, all capable of good accuracy (a few percent), but the ICRP implies (perhaps unintentionally), and the operational health physicist might be forgiven for assuming, that measurements of absorbed dose are preferred. Indeed it is true that dose equivalent is still calculated via the absorbed dose but it is, of course, not necessary to measure this latter quantity directly. The prescription of Eq. (1) has worked well in certain restricted cases, for example, the calculation of small-organ doses from absorbed

radionuclides (when several simplifying assumptions are made) or dosimetry for low-energy photons (when all QF's are unity). However, as we have seen, attempts to employ Eq. (1) or (3) directly in the practical evaluation of DE in mixed radiation fields has met with some practical difficulties. In an unknown radiation field it is necessary to

(a) measure the absorbed dose distribution through the body,

(b) evaluate the LET spectrum at the points at which the absorbed dose measurements were made,

(c) construct the dose-equivalent distribution in the body and locate its values in the critical organs.

Such a procedure although probably technically feasible, would undoubtedly be time-consuming, and may not always be necessary.

4. PRACTICE OF RADIATION DOSIMETRY

The concepts of the dosimetric units and their history having been reviewed, it is pertinent to examine the practical techniques currently used in operational health physics.

Two basic approaches to operational problems may be distinguished. The first attempts to apply Eq. (3) directly and develop instruments capable of measuring the physical quantities required. The second approach attempts to specify the radiation field in physical terms and directly calculate dose-equivalent distribution with depth without passing through the intermediate stage of measurement of absorbed dose.

4.1 Measurements of Abosrbed Dose and Evaluation of Quality Factor

Absorbed dose may be measured with a tissue-equivalent ionization

chamber by meeting the Bragg-Gray requirements that the tissue-equivalent wall be thick enough so that charged-particle equilibrium is achieved, and that the density of the gas in the cavity be low enough so that charged particles do not lose an appreciable fraction of their energy in traversing the cavity. Clearly, to insure that these requirements are met, one must either have prior knowledge of the quality of the radiation or make assumptions as to its composition. (Measurements of absorbed dose may be made with cavity chambers that do not meet the Bragg-Gray requirements but the theoretical basis for such determinations is extremely complex and in any event requires detailed knowledge of the radiation environment.) At present ICRU has not specified the construction of such chambers or their volume to facilitate convenient intercomparison of experimental data. Such a specification is, of course, a difficult problem, because the details of chamber construction depend upon the type of radiation to be measured and the sensitivity required. When such absorbed-dose measurements are made there still remains the problem of selecting an appropriate quality factor. This selection may be achieved by

(a) A measurement with an instrument such as the recombination chamber, [54-56]

(b) determination of the LET spectrum of the radiation field, or

(c) choice of some prudently conservative estimate of quality factor (because it never underestimates dose equivalent, this approximation usually results in unnecessary restrictions in operational procedures).

All three techniques have their disadvantages. The third

alternative we will not discuss further because it does not provide a satisfactory basis for routine practice. Recently the ICRU has discussed the difficulties in measuring LET spectra, and indicated that, in general, full LET distributions may be obtained only by calculation. This of course presupposes a priori knowledge of the radiation field and calculation of an appropriate quality factor.

The large discrepancies between different techniques for evaluating quality factor have been discussed in a paper from the CERN Health Physics Group.[57]

4.2 Measurement of Fluence and Dose-Equivalent Calculations

Dose equivalent may be determined if sufficient detail is obtained on the radiation field incident upon the irradiated person. Such a procedure demands

(a) Qualitative determination of the components of the radiation field -- i.e., one that reveals the types of particle incident: photons, neutrons, α particles, or whatever.

(b) Determination of the flux density, energy spectra, and angular distribution of each significant component of the radiation field in sufficient detail to permit calculation of the dose equivalent to the precision required.

In practical health physics problems we are often limited to a need to identify exposures due to photons, electrons, and neutrons. Many instruments available can discriminate between these particles. However, when instruments designed to measure absorbed dose and LET spectra are used, they can never reveal the nature of the incident radiation field, and one important aspect of the radiation exposure is

irretrievably lost.

Particle fluence and energy spectra are well-established physical concepts and may be measured with extreme precision, if required, by rather sophisticated techniques currently employed in particle research. The choice of physical techniques which quantify the radiation field in terms of particle spectra would not therefore limit the accuracy of the dose equivalent, even if the accuracy of our biological knowledge were greatly improved. (We should note here that this is not the case with measurements of absorbed dose which are limited in sensitivity, volume, or both.)

Many types of detectors have been developed for flux-density measurements with a precision acceptable for health physics purposes (about 100%). In neutron fields, BF_3 counters with different thicknesses of moderators may be used. In addition, several types of activation detectors allow neutron flux density measurements in a very broad range of energies. Such detectors are quite energy-selective and permit evaluation of neutron energy spectra with a precision adequate for the purposes of radiation protection. Scintillation counters, hydrogen-filled proportional counters, or silver-covered GM counters are also used for neutron flux density measurements. Pulsed ion-chamber proportional counters, GM counters, or scintillators are widely used for γ-ray and charged-particle flux-density measurements in a broad range of energies. Activation detectors can also be used in high energy fields. From the knowledge of the flux density versus energy those quantities required for the risk evaluation may then be calculated as will now be described.

If the composition of the incident radiation field is known to consist of n different types of particle, i, whose flux density between energy E and E + dE is $\phi_i(E)dE$, the dose equivalent rate may be defined to be

$$DE = \sum_{i=1}^{n} \int_{E_i(min)}^{E_i(max)} \frac{\phi_i(E)}{g_i(E)} \, dE, \qquad (8)$$

where $E_i(min)$, $E_i(max)$ are the minimum and maximum energies of the i particles respectively; $g_i(E)$ is a factor that converts a flux density $\phi_i(E)$ of i particles at energy E to the DE rate.

It is necessary therefore to derive values of the conversion factors $g_i(E)$. In general, the evaluation of such conversion factors is a complex matter involving the calculation of particle spectra produced from the primary particles within models of a body. Given the details of particle spectra within the tissue, one can calculate the absorbed dose in a chosen elementary volume from the known stopping power of each charged particle in tissue,

$$D = \sum_{n} \int_{z_1}^{z_2} D(z)\, dz, \qquad (9)$$

where D(z) represents the distribution of absorbed dose along the track (the energy deposited per unit length of track divided by mass of the chosen volume), and z_1 and z_2 are the limits of the track inside the volume. The $\sum_n$ represents the summation over all the ionizing particles crossing the volume. If the LET distribution along the track of each particle is known, one can weight each segment of charged-particle track by the appropriate quality factor and calculate the dose

equivalent,

$$DE = \sum_n \int_{z_1}^{z_2} QF(z)\ D(z)\ dz. \tag{10}$$

For that elementary volume, one can calculate an average $\langle QF \rangle$ as

$$\langle QF \rangle = \frac{DE}{D}. \tag{11}$$

Typically one chooses 1 cm^3 as elementary volume within the body model. One ends with a distribution of D's, QF's, and DE's inside the model as precise as present physical knowledge and present dosimetric recommendations allow. From this distribution one selects a single value of the DE's (either maximum or that at the organ of interest). From this value the g_i is easily calculated (which incidentally makes it possible to express MPD's in terms of particle flux densities). From this kind of calculation one infers also the QF's for mixed radiation fields.

Such detailed calculations, involving as they do complex details of geometry and nuclear interactions, in general need a large digital computer for their execution. Extensive effort has been devoted by the Health Physics and Neutron Physics Divisions of Oak Ridge National Laboratory to the calculation of absorbed-dose and dose-equivalent distributions in water and tissue phantoms. In general such calculations have been principally in semi-infinite uniform tissue slabs, although some work has been carried out on finite tissue cylinders and parallelepipeds.

As greater realism is demanded it seems only to be a matter of tenacity to perform calculations in phantoms accurately simulating

the structure of the human body.

5. CONCLUSIONS

The use of particle accelerators in industry, medicine, and research grows rapidly, and their number is increasing at the rate of 10% per year. There are now more than 1400 accelerators in operation in the United States alone. More and more individuals are occupationally exposed to high LET radiations.

At high energy particle accelerators, techniques for the determination of neutron spectra with accuracy sufficient for DE evaluations have been developed over the past ten years.[58, 59] The conversion of these spectra to DE is now well understood,[12, 60, 61] solving the difficulties of accelerator dosimetry discussed by Goebel et al.[57]

The problems of high LET radiation dosimetry are not limited to high energy accelerators, however they arise, whenever neutrons are to be measured. Thus Stone and Thorngate,[62] in discussing neutron dosimetry in the energy region 50 keV to 450 keV, make the following unequivocal statement: "In order to make accurate measurements of the neutron dose delivered to a medium, it is essential to have some knowledge of the incident neutron spectrum . . ." Indeed, a glance at the literature should rapidly convince the reader of the need to understand the neutron spectrum in neutron dosimetry at all energies.[63] Sidwell and Wheatley[64] in a recent paper have indicated the advantages of such a system for photon dosimetry.

We conclude it to be increasingly necessary that guidance be given to health physicists concerned with the operational problems posed by high LET radiation environments. We feel it would be a forward-looking

move to reappraise the guidance given by ICRU and ICRP with a view to clarifying the points discussed in this paper.

We consider the following three points worth serious discussion:

1. Dose Equivalent

a. ICRU should be encouraged to define the physical units of dose equivalent.

b. The ultimate radiation-protection goal to be served by this quantity should be determined. Is it the intention of ICRP to relate dose equivalent to an estimate of risk of radiation-induced disease?

c. The accuracy required in estimates of dose equivalent should be authoritatively determined.

2. Physical Measurements Required to Determine Dose Equivalent

Radiation-protection standards are given in terms of dose equivalent, and absorbed dose is of value in health physics only insofar as it leads to estimates of dose equivalent. It is our view that the definition of dose equivalent by the familiar equation

$$DE = D \times (QF) \times (DF) \text{ etc.}$$

has led to overemphasis on efforts to measure absorbed dose in mixed radiation fields. Direct measurements of absorbed dose may be helpful but present some severe practical problem in operational health physics, but estimates of QF in mixed radiation fields are impossible without knowledge of the radiation field in which measurements are to be made.

Absorbed dose is a rather sterile* concept for operational health physics. In health physics knowledge of the radiation field is required

*Sterile - producing little or nothing; unfruitful (Webster).

so that personnel exposure can be controlled by modification of the radiation field, e.g., by shielding. Thus, a fundamental understanding of radiation fields for purposes of modifying them has the fortunate bonus that calculation of absorbed dose or dose equivalent may be incidentally made with little difficulty. It seems to us that this is the most fruitful approach for practical dosimetry in mixed radiation fields.

Present physical techniques of measurement permit quantification of unpertubed radiation fields to within a few percent (essentially precise for radiation-protection purposes).

Current ICRU-ICRP prescriptions for the evaluation of dose equivalent from these accurate physical measurements are not sufficiently detailed to permit us to obtain the desired accuracy of about ± 25%.

3. Radiobiology and Radiation Protection

It must be recognized that the requirements for dosimetric units in the two disciplines of Radiobiology and Radiation Protection are often quite distinct.

ICRU has given a great deal of attention to the dosimetric requirements of radiology and radiobiology, but these are quite different from those of Health Physics. We would encourage greater attention to the problems of radiation protection, particularly with respect to definition of the field in terms of fundamental physical quantities.

The authors speculate that there is an area of overlap between ICRP and ICRU for which neither commission seems anxious to become responsible. ICRU does not appear, on the basis of its publications, to be particularly interested in sharpening up its

definitions of units for radiation protection. There are many instances in ICRU publications of failure to clarify important points crucial for accurate dosimetry in radiation protection. ICRU seems to be content to permit over-estimates in the dose equivalent by as much as a factor of 3 in the belief that limited accuracy is sufficient. On the other hand, it may be that ICRP, while hoping for precisions of about 20%, is reluctant to enter the territory of ICRU to make the necessary improvements in definitions needed.

At present our knowledge of fundamental radiobiology does not permit precise estimates of risk from radiation exposure at the levels pertinent to radiation protection. Radiation-protection standards are therefore only tenuously linked to fundamental biology. Radiobiology is a young discipline, and its concepts have not yet been stabilized. It is perhaps too early to take over its concepts -- which will probably change with time as our knowledge becomes deeper -- directly into radiation protection. Rather it is preferable to assign the broad goals of radiation protection, and to compensate for the lack of precise detail by clearly recognized administrative decisions.

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REFERENCES

1. International Commission on Radiological Protection, ICRP Publication No. 9, Recommendations of the International Commission on Radiological Protection (Pergamon Press, 1966, p. 1, par. 3.
2. P. R. Bevington, Data Reduction and Error Analysis for the Physical Science (McGraw-Hill, N. Y. 1969).
3. International Commission on Radiological Units, ICRU Report 11, Radiation Quantities and Units, 1968. ICRU Washington.
4. International Commission on Radiological Protection, ICRP Publication No. 12, General Principles of Monitoring for Radiation Protection of Workers, (Pergamon Press, 1969) p. 17 par. 101.
5. L. D. G. Ritchings, Policy and Standards, The ICRP Round-Table Discussion in "News and Comments-Brighton-Special," Ed. H. J. Dunster, Health Physics 19, 361 (1970).
6. H. W. Patterson and R. H. Thomas, Quality Factor-A Sound Concept?, Health Physics 20, 529 (1971).
7. H. J. Dunster, Some Problems in the Application of ICRP Maximum Permissible Levels for Occupation Exposure, Health Phys. 12, 77 (1966).
8. B. M. Wheatley, A Question of Interpretation, Health Phys. 14, 599 (1968).
9. J. Neufeld, Comments on Quality Factor, Health Phys. 17, 625,(1969).
10. J. Neufeld, Radiation Quantities and Their Significance in Health Physics, Parts 1 and 2, Health Phys. 19, 253 (1970).

11. S. Prêtre, Neutron Depth Doses in Man and Corresponding Quality Factors, Forschungs Institut fur Militarische Bautechnik, Zurich, Internal Report FMB 70-16, October 1970.

12. H. W. Patterson, J. T. Routti, and R. H. Thomas, What Quality Factor?, Health Physics 20, 517 (1971).

13. H. J. Dunster, Quality Factor-A Sound Concept, Health Physics 20, 529 (1971).

14. J. Neufeld, Reply to H. J. Dunster on "Quality Factor—A Sound Concept," Health Physics 20, 530 (1971).

15. H. O. Wyckoff, Comments on "Radiation Quantities and Their Significance in Health Physics, Parts 1 and 2," Health Physics 20, 669 (1971).

16. J. Neufeld, Metrology in Health Physics and the ICRU, Oak Ridge National Laboratory preprint, 1971.

17. H. J. Dunster, Some Further Thoughts on Dose and Quality Factor in Radiological Protection, National Radiological Protection Board (Harwell, U.K.) Internal Report, June, 1971.

18. J. Neufeld, Dosimetric Quantities in Health Physics, Health Physics 21, 97 (1971).

19. J. Neufeld, What is Energy Imparted?, Health Physics 21, 317 (1971).

20. B. M. Wheatley and T. E. Burlin, Radiation Quantities in Health Physics, Health Physics 21, 609 (1971).

21. International Commission on Radiological Protection, ICRP Publication No. 14, Radiosensitivity and Spatial Distribution of Dose, (Pergamon Press, 1969), Sect. 6.

22. W. C. Roentgen (First Communication) Erste Mitt. Sitzungsberichte

der Würzburger Physik-Medic Geseffschaft 137 (December 1895), Translated first by A. Stanton in Nature 53, 274 (January 23, 1896), and published also in Science 59, 227 (February 14, 1896) and other magazines. Roentgen's first communication was continued in a second paper published in Sitzungsberichte der Würzburger Physik-Medic Geseffschaft (March 9, 1896) and translated in Science Vol. III, 72, 726 (May 15, 1896) and other magazines.

23. O. Glasser, W. C. Roentgen and the Early History of the Roentgen Rays (Charles C. Thomas, Springfield, Ill., 1934).
24. E. H. Grubbe, Radiology 21, 156 (1933). Several other cases of early injuries are reported in R. S. Stone Radiology 58, 5, 639 (May 1952).
25. P. Brown, American Martyrs to Science Through Roentgen Rays (Charles C. Thomas, Springfield, Ill., 1936).
26. A. C. Upton, Radiation Injury (University of Chicago Press, Chicago, 1969).
27. K. Z. Morgan, History of Damage and Protection from Ionizing Radiation, in Principles of Radiation Protection, edited by K. Z. Morgan and J. E. Turner (John Wiley and Son, New York, 1967), Chapter 1.
28. D. Glasser, E. H. Quimby, L. S. Taylor, J. L. Weatherwax, and R. H. Morgan, Physical Foundation of Radiology (P. B. Hoeber, Inc., New York, 1961), Chapter 1.
29. International X-Ray Unit of Intensity, Brit. J. Radiol. 1, 363 (1928).
30. W. C. Roesch and F. H. Attix, Basic Concepts of Dosimetry, in Radiation Dosimetry, Vol. 1, edited by F. H. Attix and

Roesch (Academic Press, New York, 1968), Chapter 1.

31. ICRU, Recommendations of the ICRU, Chicago, 1937, Am. J. Roent. Radium Therap. Nucl. Med. 39, 295 (1938).

32. ICRU, Report of the International Commission on Radiological Units and Measurement (1956), in National Bureau of Standards Handbook NBS No. 62, 1957.

33. ICRU, Radiation Quantities and Units, Report 10a of the International Commission on Radiological Units and Measurements, in National Bureau of Standards Handbook, NBS No. 84, 1962.

34. A. Mutscheller, Am. J. Roent. Radium Therapy 13, 65 (1925).

35. H. E. Johns, Use of X and Gamma Rays in Radiotherapy, in Radiation Dosimetry Vol. 3, edited by F. H. Attix and E. Tochilin (Academic Press, New York, 1969), Chapter 30.

36. D. E. Lea, Actions of Radiation on Living Cells (University of Cambridge Press, London 1956), p. 21.

37. P. C. Aebersold and J. H. Lawrence, Ann. Rev. Physiol. 4, 25 (1952).

38. L. H. Gray, Proc. Cambridge Phil. Soc. 40, 72 (1944).

39. Ref. 1, Sect. 10.

40. H. M Parker, Health, Health Physics Instrumentation and Radiation Protection, Advan. Biol. Med. Phys. 1, 243 (1948).

41. Report of the RBE Committee to the ICRP on Radiological Units and Measurements, Health Phys. 9, 357 (1963).

42. R. E. Zirkle, D. F. Marchbank, and K. D. Kuck, J. Cellular Comp. Physiol. 39, Suppl. 1, 75 (1952).

43. Ref. 3, Chap. II.

44. H. H. Rossi, Microscopic Energy Distribution in Irradiated Matter, in Radiation Dosimetry, Vol. I, edited by F. H. Attix and W. C. Roesch (Academic Press, New York, 1968).

45. H. H. Rossi and G. Failla, Tissue Equivalent Ionization Chambers, Nucleonics 14[2], 32 (1956).

46. J. Baarli and A. H. Sullivan, Health Phys. 11, 353 (1965).

47. International Commission on Radiological Protection, Report of Subcommittee I on Permissible Doses for External Radiation (1954). Also see Ref. 41.

48. International Commission on Radiological Protection, ICRP Publication No. 15, Protection Against Ionizing Radiation From External Sources (Pergamon Press, London, 1970).

49. International Commission on Radiation Units and Measurements, ICRU Report No. 16, Linear Energy Transfer, 1970, Chapter 7.

50. H. H. Rossi and W. Rosenzweig, A Device for the Measurement of Dose as a Function of Specific Ionization, Radiology 64, 404 (1955).

51. E. Freytag and D. Nachtigall, A Comparison of Health Physics Measuring Procedures at Accelerators, Deutsches Electroken-Synchrotron, Internal Report DESY/70/27 (1970).

52. Ref. 3, Chapter II, p. 2.

53. T. E. Burlin, Cavity-Chambers Theory, in Radiation Dosimetry Vol. 1, edited by F. H. Attix and W. C. Roesch (Academic Press, New York, 1968).

54. M. Zelchinskii, Instr. Exptl. Tech. (USSR) (English Transl.) 6, 1217 (1964).

55. A. H. Sullivan and J. Baarli, An Ionization Chamber for the

Estimation of the RBE of Radiation, CERN 63-17, 1963.

56. S. Pszona, A New Approach for Determining Quality Factor and Dose Equivalent in Mixed Radiation Fields, Health Phys. 16, 9 (1969).

57. K. Goebel, A Rindi, et al., The Purpose, Interpretation, and Utilization of Area-Monitoring Measurement near the CERN Accelerators, in Proceedings of Symposium on Radiation Dose Measurements held by ENEA, Stockholm, 1967, p. 435.

58. W. S. Gilbert et al., 1966 CERN-LRL-RHEL Shielding Experiment at the CERN Proton Synchrotron, Lawrence Radiation Laboratory Report, UCRL-17941, September 1968.

59. Jorma T. Routti, High Energy Neutron Spectroscopy with Activation Detectors, Lawrence Radiation Laboratory Report UCRL-18514, April 1969.

60. Op cit Ref. 58, Chapter IX.

61. K. B. Shaw, G. R. Stevenson, and R. H. Thomas, Health Physics 17, 459 (1969).

62. D. R. Stone and John H. Thorngate, The Development of a Spectrometer and the Measurement of the Neutron Spectrum from the Health Physics Reactor Between 50 keV and 450 keV, Health Physics 21, 441 (1971).

63. See for example: Neutron Dosimetry, Vols. 1 and 2, Proceedings of the Symposium on Neutron Detection, Dosimetry, and Standardization, Harwell, December 10-14, 1962, Published IAEA, Vienna (1963).

64. J. M. Sidwell and B. M. Wheatley, Calculation of the Absorbed Dose in a Phantom from Photon Fluence and Some Applications to Radiological Protection, Brit. J. Radiol. 42, 522 (1968).

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