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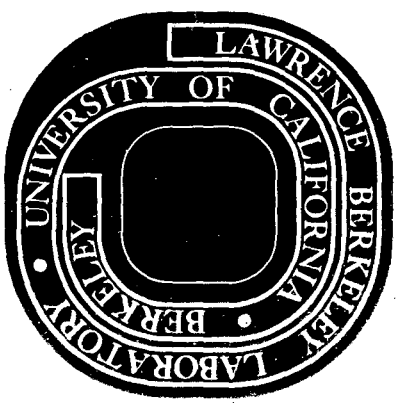

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ABSORBED DOSE--AN UNFORTUNATE "RED HERRING"* IN RADIATION PROTECTION

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ABSTRACT

Man's uses of ionizing radiations are increasing rapidly, and, in particular, larger numbers of people are being exposed to high linear energy transfer (LET) radiations. These radiations present interesting problems of dosimetry which are discussed in the light of the authors' experience at high energy accelerators.

It is suggested that two aspects of our present scale for numerical expression in radiation protection need clarification. Firstly, the physical dimensions of dose equivalent (DE) should be defined and secondly, the precision with which DE estimates are to be made should be stated. The practical evaluation of DE in mixed radiation fields is discussed and it is suggested that this quantity is better obtained via measurements of particle flux density and energy spectra than by LET spectrometry. The advantages of the former technique over the latter are discussed briefly.

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*Red Herring--something used to confuse or direct attention from something else: from the practice of drawing a smoked herring across the trace in hunting, to distract the hounds." Webster.

INTRODUCTION

Man's uses of ionizing radiation in research, industry, and medicine have increased dramatically over the past decade. Although the major contribution to man-made exposure is still due to low LET radiations, an increasing proportion of people are being exposed to high LET radiations. Burrill has documented the increasing uses of accelerators in industry and medicine,[1,2] and shows the number of accelerators in use to be increasing at a rate of roughly 10% per annum.

Many of the electron accelerators presently being installed are of sufficiently high energy to produce neutrons, and the use of D-D and D-T neutron generators is now widespread. Radiotherapy with π-mesons and energetic heavy ions is gaining interest; when brought to fruition occupational exposure of considerable numbers of hospital personnel will result. The use of high flying aircraft for mass transportation will expose large numbers to high LET radiations[3] and--if we anticipate somewhat--space flights will expose passengers to the scarcely shielded primary galactic radiation.

Man's ability to produce a wide variety of radiation environments is not at debate;[4] it seems to us highly probable that these radiations will be applied rapidly, particularly in industry and medicine, to a host of diverse tasks. In consequence we anticipate a growing interest in the problems of health physics posed by these new environments.

We believe it would be a forward-looking move to review critically the present recommendations of ICRP and ICRU, with a view to identifying what problems, if any, will arise from their application to high LET radiation fields.

This paper discusses some of the difficulties we anticipate in the light of our experience with many particle accelerators in the high

energy range. In particular, we suggest that the present emphasis on absorbed dose in the prescriptions by ICRU/ICRP for dose-equivalent (DE) evaluation may divert attention from more profitable avenues of approach. This is not a frivolous or eccentric whim on our part. An examination of the literature will demonstrate an increasing interest in these matters. During the past few years several authors have reviewed critically the recommendations of both the ICRP and ICRU from the standpoint of practical implementation.[5,6,7] During the last twelve months the number of papers discussing the application of radiation standards "in the field" has increased dramatically showing an expanding awareness of the practical problems involved.[8-19] Indeed, a recent ICRP Task Group itself has shown awareness of some inconsistencies in the present logical basis for the formulation of radiation standards.[20]

We restrict our comments here to external, whole-body radiation exposures and emphasize that we have no a priori knowledge in these new radiation environments that might greatly simplify our measurements. Indeed, it has been our experience with high energy accelerators that a variety of radiation environments is possible, depending upon operational conditions.

In a review such as this we have the alternatives of referring the reader to the literature or of giving extensive quotations. We have adopted the latter alternative which, although having the disadvantage of protraction, is more convenient for the reader.

A SCALE FOR NUMERICAL EXPRESSION IN RADIATION PROTECTION

"The objectives of radiation protection are to prevent acute radiation effects and to limit the risks of late effects to an acceptable level."[21] These objectives are achieved by:

a. The "unequivocal specification of a scale that may be used for numerical expression in radiation protection."[22]

b. An estimation of the risk to large human populations resulting from chronic exposure to ionizing radiation and its expression on this numerical scale.

c. A judgment of the level of risk that an informed society will tolerate in exchange for the beneficial uses of radiation, and again its expression in terms of the scale.

d. The specification of radiation safety standards on this numerical scale that will set the estimated risk no higher than that tolerated by society.

e. The demonstration that these safety standards have been satisfied by measurements (expressed on this numerical scale) of the radiation environments to which people are exposed. Such measurements will indicate what remedial actions are necessary, if any, to reduce exposures.

This paper largely deals with the first and last of these five points. Any "scale for numerical expression" we adopt should be soundly based on the best available data pertinent to human response to ionizing radiation at low doses and dose rates; it should be readily practicable and capable of being applied to all radiation environments.

In this section we examine the theoretical basis of a scale for numerical expression, and, in later sections, discuss our present scale, which is based on absorbed dose, and its practical realization in operational health physics.

Index of Radiation Risk

In an ideal situation our numerical scale would provide an index for direct expression of the risk due to radiation exposure.

Our present understanding of human radiobiological phenomena, particularly at low chronic exposures, is inadequate to permit any accurate estimate of risk. In the absence of a complete understanding of the biological consequences of the interaction of radiation with living

organisms we might speculate how such an index could be empirically obtained.

Comparison of morbidity and mortality statistics between a very large unirradiated "control" population and large populations irradiated in carefully controlled ways would provide indices of risk for differing conditions of irradiation. Such a proposal is, of course, both immoral and absurdly impracticable.

At the present time, of necessity, we obtain our estimates of radiation risk by extrapolation from data obtained at high acute exposures on the basis of the linear dose response, no-threshold model. Any index of risk so derived will be compounded of three elements, the first element representing the physical characteristics of the radiation fields, the second representing factors derived from radiobiology and the third element consisting of administrative factors which express the caution necessary in extrapolating our imprecise radiobiological knowledge to the field of radiation protection.

This might be expressed in the form

$$R = [A]\,[B]\,[P], \tag{1}$$

where R is the risk of radiation-induced disease,

[A] represents administrative factors.

[B] represents biological factors, and

[P] represents the physical characteristics of the radiation field.

At the present time because our knowledge of the biological parameters [B] is extremely limited we could conveniently combine them with the administrative factors [A] into a single factor [A'], which would be, of necessity, somewhat arbitrary and only broadly related to biological effects,

$$R' = [A']\,[P]. \tag{2}$$

Equation (2) strongly suggests that our scale for numerical

expression in radiation protection must be based on some physical parameter(s) of the radiation field. How closely measurements based on this scale ([A'][P]) correspond with the "true" risk [R] we cannot, at present, determine.

Accuracy of Risk Estimates and the Precision of Radiation Measurements

Our present ignorance of the biological effects of low levels of radiation on humans, militates against accuracy in our estimates of risk. Indeed, scientific honesty demands that we admit we do not yet know whether low level radiation exposures are harmful, are of no consequence, or are even beneficial to mankind.

It is therefore quite conceivable that estimates of risk derived from the acute, high-dose human data may be too high by considerably more than an order of magnitude. The "accuracy" of our present-day risk estimates are largely determined by how closely the administrative factors [A' in Eq. (2)] correspond to real life. This recognition of the inaccuracy inherent in our estimates of risk have led some to suggest that only limited accuracy is needed in radiation protection measurements.

This question of the accuracy needed in radiation protection measurements is of great importance in any discussion of the practical realization of any numerical scale. The present authors have suggested elsewhere[23] that the difference between the absolute accuracy with which an index of radiation risk can be specified, and the precision with which it may be reproduced has led to some confusion in the literature. The situation is quite analagous to that which obtained when scales of temperature were established prior to Kelvin's thermodynamical studies. Relative temperatures could be compared and thermal conditions reproduced with great precision independent of any knowledge of the absolute temperature. The

accuracy of our specification of radiation risk is determined by our knowledge of biology and is, at the present time, very poor. The precision with which we can reproduce radiation environments (and, presumably therefore, conditions of risk) is determined by the accuracy with which we can make physical measurements and the care with which our administrative factors ([A'] in Equation 2) are specified.

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 (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). No authoritative opinion has been published on this matter by the advisory bodies responsible for radiation protection; the closest advice that has been publicly offered, to the authors' knowledge, was given by an ICRP panel at the IRPA Congress held in Brighton in 1970. Members of the panel 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%.[12,24]

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 specification of the administrative factors in Equation (2).

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.

Numerical Scale for Radiation Protection

In summary, the logical basis for a numerical scale in radiation protection would be one of radiation risk. Limitations in our knowledge of the biological effects of radiation prevent this being done with any accuracy at the present time. We are forced, then, to improvise using some physical property (or properties) of radiation fields as the basis of our numerical scale. The determination of the relationship between these physical parameters and actual risk resulting from radiation exposure remains as one of the outstanding goals of health physics.

The precision with which the numerical scale must be reproduced is of paramount importance because it bears directly on one's attitude toward the techniques of dosimetry required for the realization of protection standards, and we urge the consideration of this matter by ICRP.

As we shall discuss in the following section, it has been found convenient to base our present scale on the evaluation of absorbed

dose [(modified by factors including that dependent on linear energy transfer (LET)]. Absorbed dose, although convenient as the basis for a numerical scale at the present time has not yet been established as of fundamental interest in radiation protection.

ICRP has endorsed two, basically different, experimental techniques for measurement on the numerical scale.[25] The first involves determination of absorbed dose (and any appropriate modifying factors), while the second (in the case of neutrons and protons) demands the measurement of particle fluence. It is the latter technique that the authors believe is capable of producing the experimental basis for a general scheme of radiation dosimetry.

ABSORBED DOSE--THE PRESENT BASIS OF OUR NUMERICAL SCALE IN RADIATION PROTECTION

Our present numerical scale in radiation protection is based upon the determination of absorbed dose (or absorbed dose, weighted by various factors). This choice of absorbed dose as the physical parameter ([P] in Eq. 2) was influenced by the historical development of radiology and radiobiology.[15] It was argued that energy absorption in the tissue of interest was the major parameter in determining radiation effects. Eventually it became clear that absorbed dose alone was an inadequate parameter. Experimentally it was shown that equal absorption of energy does not produce equal probability of any given biological effect (within factors of ten in some instances for mammals.)

It was necessary to weight the absorbed dose in some way, depending upon the characteristics of the radiation. The subsequent definitions of relative biological efficiency (RBE), RBE dose and DE is well documented in the literature. (The authors are reminded of the Shavian critique of the writing of Pavlov describing his researches on the conditioned reflex.)[26] It will be remembered that the concept of RBE dose was obtained by transforming the separate contributions to the absorbed dose into a "biologically equivalent" absorbed dose, due to some standard radiation, by application of an empirically determined RBE. Thus the biological effects of irradiation by different types of radiation would be identical to that from

$$\sum_{i=1}^{i=n} (RBE)_i \, D_i \quad \text{rads of standard radiation} \tag{3}$$

$$(RBE)_i = D_x / D_i \tag{4}$$

where D_x and D_i are the absorbed doses of standard radiation and the i^{th} radiation required to produce the same biological effects. RBE dose has evolved into the quantity now used in radiation protection, that of

dose equivalent (equivalent dose?), which is now the basis for our present numerical scale for radiation protection.

ICRU gives the following definition: "DE is defined as the product of absorbed dose-D, quality factor-QF, absorbed-dose distribution factor-DF, and other necessary modifying factors"[28] leading to the well-known equation,

$$DE = D \times (QF) \times \ldots \tag{5}$$

more recently modified (in ICRP publication 15)[29] to

$$DE = D \times QF \times (MF)_1 \times (MF)_2 \times \ldots (MF)_i, \tag{6}$$

where the symbols are so well known that they need not be explained. Unfortunately, as several authors have indicated, this definition is incomplete.[8, 9, 15] One particularly important aspect left undefined is the physical dimensions of DE.[22] It seems evident, however, from the evolution of the concept that, as presently defined, DE has the same physical dimensions as absorbed dose. It is evident from Eqs. (3) and (4) that RBE dose has the physical dimensions of absorbed dose, and it would appear reasonable that DE would have the same physical dimensions).

If this argument is accepted then it would be appropriate to define DE in a manner analogous to the definition of Exposure. We suggest that an appropriate basis for a definition might be:

"In radiation protection, dose equivalent is a measure of radiation based upon its ability to induce disease in humans chronically irradiated at low levels." In completely specifying the term it would be necessary to agree on the meaning of the terms "disease","chronically irradiated" and "low levels".

Equations (5) and (6) are not significantly different but neither is sufficiently general for application to the evalution of DE in mixed radiation fields. They seem to be predicated upon assumptions of the very special irradiation conditions commonly found in radiotherapy

or radiobiology. However, as Wheatley[30] has indicated, irradiation conditions in radiotherapy or radiobiological experiments are usually better controlled and understood (with respect to the nature of radiation. beam intensity, and direction, etc.) than the conditions found in operational health physics. Here the irradiation conditions may be extremely variable with respect to space, time, and type of radiation in which case it is necessary to understand in some detail the distribution of energy absorption throughout the body so that the actual organ dose may be compared with the MPD recommended by ICRP.[31]

Equation 5, which is in fact the true "red herring" of our title, is most frequently used to estimate DE under conditions of irradiation which make its use trivial. The particular values assigned in the QF-LET relationship[32] insure that the radiations responsible for the greater part of external radiation exposures--β particles and relatively low energy x- and γ-rays--will all have effective quality factors of 1.0. With none of the modifying factors defined and written equal to unity absorbed dose and DE become identical.

It is when Eq. (5) is used as the basis for the experimental determination of DE in mixed radiation fields, whose components cover a broad spectrum of energy, that its limitations become obvious! Such fields will produce particles with a wide range of LET. Recognizing this fact and eliminating the distribution factor, DF, from Eq. (5), DE can be expressed by the familiar equation[32]

$$DE = \int_0^{L_{max}} D(L)QF(L)dL, \qquad (7)$$

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 of interest.

Equation (7) represents the theoretical basis for the evaluation of DE at any point in tissue and we discuss in the next section the practical determination of the parameters D(L) and QF(L) necessary for its calculations.

Recently Dunster[17] has argued against the complexity of such prescriptions:

"Whether we use absorbed dose as it stands or go further into complexity is a matter of choice, depending principally on how well absorbed dose correlates with risk and severity of effect. We must also ask how close this correlation has to be in order to make it useful. I believe that a reasonable case could be made out for saying that absorbed dose correlates as well as can be expected with risk and that the refinements which we have commonly been using to improve the correlation do not really earn their keep. I think we have to accept the fact that some permissible exposures will always be more permissible than others." If we understand Dunster's arguments correctly, then we cannot agree with them, since it seems to us that they would lead directly either to a reduction in currently recommended MPD's by about an order of magnitude to cover all possible exposures, or to a general admission that MPD's were already overly conservative (by about an order of magnitude) for low LET radiation exposures. There are sound economic reasons for differentiating between exposures due to different types of radiation.

THE PRACTICAL EVALUATION OF DE

The practical problem of DE evaluation, as presently defined, reduces to a determination of the integral of Eq. (7) to the desired accuracy (assumed to be ~25% in this paper).

At a time when digital computers were unavailable, recourse to experimental techniques, which attempted to measure D(L) as a function of LET, seemed the most straightforward approach. However, it is not necessary, with the advent of the computer, to measure this quantity directly because it can be calculated from suitable physical parameters of the radiation field. It is a tactical question, therefore, as to which technique is used to evaluate DE. We attempt to show in this paper that any technique of dosimetry in mixed radiation fields, if it is to be accurate, requires knowledge of particle flux density and energy spectra for its interpretation.

The ICRP has never specified that experimental determinations of DE must be obtained through measurements of absorbed dose. Indeed, as we have already indicated, it has endorsed the experimental technique of particle-flux density determination for neutrons and protons. Nevertheless, one might be forgiven for assuming that the direct measurement of D(L) distributions is the experimental technique preferred by the ICRP/ICRU. Great prominence is given to Eq. (5) in the publications of these bodies. In addition, the joint ICRP/ICRU RBE committee has specifically recommended the use of LET spectrometers in the evaluation of DE "in the vicinity of GeV accelerators."[32,33] (See Appendix.)

Unfortunately, the experimental technique promoted by the RBE committee (admitted by them to be complex) is not experimentally convenient for routine operation, neither is it specified with sufficient accuracy for application to dosimetry at high energy accelerators. A recent survey by Freytag and Nachtigall[34] 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. An adequate DE evaluation becomes extremely laborious when such instruments are used.

The present authors[35] have described the detailed steps necessary in expediting such a determination as:

a. to measure the absorbed dose distribution through the body;

b. to evaluate the LET spectrum at the points at which the absorbed dose measurements were made, and,

c. to construct the DE distribution in the body and determine its value in the critical organs of the body and/or at its maximum.

Even the first requirement--that of measuring absorbed dose--has some difficulties. Dennis[36] in a familiar quotation pointed out that we cannot measure absorbed dose directly.* Only one instrument allows absolute measurement of absorbed dose, the calorimeter, which is too insensitive at the dose rates encountered in health physics. One thus is forced to use indirect experimental techniques to measure absorbed doses in radiation protection. Absorbed dose may be indirectly measured with a tissue-equivalent ionization chamber meeting the Bragg-Gray requirements. Unfortunately, in order that an instrument satisfying these requirements can be constructed, one must have prior knowledge of the quality of the radiation field to be measured.[37]

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*"Once upon a time we had the roentgen, which we could measure but didn't want; then we had the rad, which we wanted but couldn't measure; and now we've got kerma, which we don't want and can't measure."

Even when such absorbed-dose measurements are made, there still remains the problem of selecting an appropriate QF. This selection may be achieved by either

a. measurement with an instrument such as the recombination chamber,[38-40] or

b. determination of the LET spectrum of the radiation field,[41] or

c. choice of prudently conservative estimate of QF (because it never underestimates DE this approximation usually results in unnecessary restrictions in operational procedures).

All three techniques have their disadvantages. The third alternative does not provide a satisfactory basis for routine practice, while the first has not found wide favor at accelerator laboratories.[34]

Despite the development of a spherical proportional counter for use as an LET spectrometer by Rossi and his colleagues,[41] LET spectrometry is such an extremely difficult technique that a recent ICRU report concludes that, in general, LET distributions must be calculated.[42] We can only calculate the LET distributions in tissue if the physical nature of the radiation field is known in which the body is situated. But, if the latter is known, the absorbed dose distribution may also be calculated, making measurements of this parameter redundant. One is therefore inevitably led to the conclusion that a general system of dosimetry should be based upon the determination of physical parameters of radiation fields. The RBE committee hinted at this when they wrote: "Most practical DE problems consist in the evaluation of the hazard due to a mixture of neutrons and gamma radiations. The QF of neutrons as a function of neutron energy has been evaluated for neutron energies up to 10 MeV.* If the neutron energy distribution is known, the absorbed dose due to neutrons may then be multiplied by an appropriate QF to obtain the DE."[43]

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*Authors' comments: At the time of writing (1963).

SUMMARY:
PRACTICAL DOSIMETRY IN MIXED RADIATION FIELDS

In closing we should perhaps attempt to justify the title of this paper. (Just as it is easier to write sensational menus than to cook an excellent dinner, so is it difficult to fulfill the promise of a sensational title!) However, we do feel that, as our title suggests, absorbed dose has provided a diversion, particularly for operational health physicists, usurping energies which might have been more fruitfully directed.

The actual bases for using absorbed dose and DE in setting up a numerical scale for use in radiation protection are scant. It is debatable whether it was prudent to impose a specific radiobiological model on the discipline of health physics at such an early stage of its development. We have already alluded to the subsequent modifications found necessary to improve the model somewhat to provide a numerical scale for expression in radiation protection. Recently Rossi has suggested that LET has "only limited usefulness and that its various distributions have in fact no physical reality."[44] It is entirely possible that as our knowledge of radiobiology increases it may become clear that absorbed dose per se has very little relevance to radiation protection. Mayneord has recently reiterated his earlier suggestion that integral dose (the product of the absorbed dose and the mass integrated throughout the body) or the product of the square of the absorbed dose and the mass integrated throughout the body, may be important physical parameters in carcinogenesis.[45,46] We cannot be sure what physical parameters may eventually be identified as relevant to radiation protection. There are sound practical reasons for obtaining a complete physical description of radiation fields, from which any physical parameters of interest may be calculated.

At the practical level absorbed doses cannot be measured with absolute instruments, at the dose rates experienced in radiation protection. The calibration of indirect instruments can present technical difficulties, particularly in mixed radiation fields. The major technical difficulty arises from attempts to evaluate the integral

$$\int QF(L)\, D(L)\, dL$$

with good accuracy. It is upon this point that the question of the precision desired in our scale of radiation protection bears so heavily. If this integral need be evaluated only to within a factor of about 3, approximations are permissible which relax the skill required of radiation measurement. However, if this integral should be determined to ± 25%, then it will be necessary to calculate the LET distribution. Since this may be done only from a knowledge of the composition of the radiation field, any technique which tries to measure LET distributions, rather than having any advantage of simplicity, is unnecessarily complex.

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. In any event, operational health physics comprises more than dosimetry alone. We have never understood why the point that "no explicit knowledge or energy of the radiation is required" should be extolled as an advantage. Control of radiation exposures by the modification of radiation environments (shielding) requires some detailed specification of the radiation field. Thus, a fundamental understanding of radiation fields for purposes of modifying them offers the fortunate bonus that calculation of absorbed dose or DE may be made incidentally with little difficulty. It seems to us that this understanding offers the most fruitful approach for practical dosimetry in mixed radiation fields.

At high energy particle accelerators, techniques for the determination of neutron spectra with accuracy sufficient for DE evaluation have been developed over the past ten years.[47,48] The conversion of these spectra to DE is now well understood,[9,49,50] solving the difficulties of accelerator dosimetry discussed by Goebel et al.[51] The particle flux densities may be related to DE and absorbed-dose distributions by Monte Carlo calculations of the nuclear interactions within the human body. 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 DE distributions in water and tissue phantoms.[52] 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.

At lower energies Stone and Thorngate,[53] 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.[54] Sidwell and Wheatley[46] in a recent paper have indicated the advantages of such a system for photon dosimetry.

In conclusion we believe it to be increasingly necessary that guidance be given to health physicists concerned with the operational problems posed by high LET radiation environments. Some theoreti-

cal uncertainties are apparent in our present numerical scale in radiation protection, based as it is upon evaluation of modified absorbed dose. We have suggested here that DE is a crude measurement of radiation based upon its biological damage to humans. There is much to be gained by a careful reappraisal of what role is intended for DE in radiation protection. We urge in particular:

a. that physical dimensions of DE be defined, and

b. that ICRP consider giving guidance as to the precision required in the estimate of DE at levels close to the MPD.

Having considered these points it remains to discuss the practical evaluation of DE. Recommendations should be given which enable the translation of measurements made with the more frequently used experimental techniques to DE with the precision required. We urge that the ICRP seriously consider expanding its studies of the practical problems of radiation dosimetry in mixed radiation fields, with a view to developing practical and unequivocal techniques of dosimetry. This will necessitate consideration of the problem of the conversion of particle flux density and energy spectra data into DE.

We look forward to the day when, after these problems have been considered, our numerical scale of expression can be specified in terms of radiation field quantities alone, without the necessity of invoking only specific biological models.

APPENDIX

Report of the RBE Committee--Paragraph 86

"It is useful to consider the practical problem of the assessment of DE in radiation protection surveys, since this may be carried out in a variety of ways and the choice between these will depend on the practical situation encountered. The accurate evaluation of DE requires a dermination of absorbed dose as a function of LET. A technique has been devised[41] to determined D(L) for particles other than electrons at LET values >3.5 keV/μ. Since the QF for virtually all electrons encountered in practice, and for any particles having LET <3.5 keV/μ, is equal to unity, one may determine the $D(L)_\infty$ above this limit and subtract the integral

$$\int_{3.5}^{\infty} D(L)dL$$

from the total absorbed dose,

$$\int_{0}^{\infty} D(L)dL,$$

as measured with a tissue-equivalent ionization chamber. In this way it is possible to obtain the absorbed dose delivered at an LET <3.5 keV/μ, which is given a QF of unity, and then to evaluate the integral

$$\int_{3.5}^{\infty} D(L)\ QF(L)\ dL.$$

The total DE is given as the sum of these two terms. This method has the advantage that no explicit knowledge of the nature or energy of the radiation(s) is required and, for this reason, it is particularly useful in very complicated radiation fields such as exist in the vicinity of

GeV acclerators. Furthermore, because it is the most exact method, it always results in the lowest value of DE since simplifications must be conservative and thus lead to overestimates. On the other hand, because of the complexity of the method and the extensive measuring equipment requirements this approach is, at present, rarely used."

REFERENCES

1. E. A. Burrill, World-wide Usefulness of Particle Accelerators, NUCLEX-66, International Nuclear Exposition, Basel, Switzerland, September 1966.
2. E. A. Burrill, The Expanding Use of Particle Accelerators in Research, Medicine, and Industry, A Statistical Review, in Proceedings of the Second International Conference on Accelerator Dosimetry and Experience, CONF-691101, Stanford, Calif., November 5-7, 1969.
3. H. J. Schaefer, Radiation Exposure in Air Travel, Science 173, 780 (1971).
4. L. Rosen, Relevance of Particle Accelerators to National Goals, Science 173, 490 (1971).
5. H. J. Dunster, Some Problems in the Application of ICRP Maximum Permissible Levels for Occupation Exposure, Health Physics 12, 77 (1966).
6. B. M. Wheatley, A Question of Interpretation, Health Physics 14, 599 (1968).
7. J. Neufeld, Comments on Quality Factor, Health Physics 17, 625 (1969).
8. J. Neufeld, Radiation Quantities and Their Significance in Health Physics, Parts 1 and 2, Health Physics 19, 253 (1970).
9. H. W. Patterson, J. T. Routti, and R. H. Thomas, What Quality Factor?, Health Physics 20, 529 (1971).
10. S. Pretre, Neutron Depth Doses in Man and Corresponding Quality Factors, Forschungs Institut fur Militarische Bautechnik, Zurich, Internal Report FMB 70-16, October 1970.
11. H. J. Dunster, Quality Factor-A Sound Concept, Health Physics 20, 529 (1971).

12. H. W. Patterson and R. H. Thomas, Quality Factor–A Sound Concept?, Health Physics 20, 529 (1971).

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

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

15. A. Rindi and R. H. Thomas, Povera E Nudá Vai Dosimetria, Lawrence Radiation Laboratory Report, UCRL-20814, June 1971 (submitted to Health Physics).

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. International Commission on Radiological Protection, ICRP Publication # 14, Radiosensitivity and Spatial Distribution of Dose, (Pergamon Press, Oxford, 1969), Sect. 6.

21. International Commission on Radiological Protection, ICRP Publication # 9, Recommendations of the International Commission on Radiological Protection (Pergamon Press, Oxford, 1966), p. 1, par, 3.

22. International Commission on Radiological Units, ICRU Report 11, Radiation Quantities and Units, 1968, ICRU Washington-Section II.

23. Op cit Ref. 15 section 1.

24. 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).

25. International Commission on Radiological Protection, ICRP Publication #4, Report of Committee IV on Protection Against Electromagnetic Radiation Above 3 MeV and Electrons, Neutrons, and Photons (Pergamon Press, Oxford 1964).

26. G. B. Shaw, The Man of Science, Chapter 23 in Everybody's Political What's What? (Constable and Co., London, 1944).

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

28. Op cit Ref. 22, Section II, p. 2.

29. International Commission on Radiological Protection, ICRP Publication #15, Protection Against Ionizing Radiation from External Sources (Pergamon Press, Oxford, 1970).

30. B.M. Wheatley, A Unified Approach to Dosimetry Problems in Radiological Protection, Central Electricity Generating Board, Berkeley Nuclear Laboratories, U.K. Internal Report RD/B/MI655, March 1970.

31. Op cit Ref. 21, para 75.

32. Report of the RBE Committee to the ICRP on Radiological Units and Measurements, Health Physics 9, 357 (1963). (See also: Report of Subcommittee I on Permissible Dose for External Radiation, 1954.)

33. Ibid para. 86.

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

35. Op cit Ref. 15, Section 4.2.

36. J. A. Dennis, Personnel Dosimetry Techniques for External Radiation in Proceedings European Nuclear Agency Symposium Madrid, 1963, p. 207.

37. 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).

38. M. Zelchinskii, Inst. Exptl. Tech. (USSR) English Trans. 6, 1217 (1964).

39. A. H. Sullivan and J. Baarli, An Ionization Chamber for the Estimation of the RBE of radiation, CERN 63-17 (1963).

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

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

42. International Commission on Radiation Units and Measurements, ICRU Report #16, Linear Energy Transfer, 1970, Chapt. 7.

43. Op cit Ref. 32, para. 87.

44. H. H. Rossi, Linear Energy Transfer and Microdosimetry, Proc. Symposium on Neutrons in Radiobiology, Oak Ridge, Tennessee, Nov. 11-14, 1969, CONF-691106.

45. W. V. Mayneord, Brit. J. Radiol. 41, 241 (1968).

46. 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).

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

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

49. Op cit Ref. 47, Chapt. IX.

50. K. B. Shaw, G. R. Stevenson, and R. H. Thomas, Health

Physics 17, 459 (1969).

51. 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.

52. J. A. Auxier et al., Neutron Interactions and Penetrations in Tissue, in Radiation Dosimetry, Vol. 1 (Academic Press, New York 1968), Chapter 6.

53. 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).

54. 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).

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