RADIATION PROTECTION QUANTITIES FOR EXTERNAL EXPOSURE

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Edited by
G. BURGER, H.G. EBERT, D. HARDER, R. KRAMER and S. WAGNER

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CONSIDERATIONS THAT LED TO THE INTRODUCTION OF THE DOSE-EQUIVALENT INDEX

A.M.Kellerer
Institut für Medizinische Strahlenkunde der Universität Würzburg,
Versbacher Str.5, D-8700 Würzburg

Introduction

The adoption of the International System of Units has - apart from certain inconveniences - the positive effect that, along with the units, fundamental quantities are reconsidered in various fields. The present symposion, although motivated by additional, practical necessities, reflects such a reconsideration in the area of radiation protection.

The lively discussion provoked by the somewhat unconventional nature of the new index quantities makes it appropriate to reexamine certain considerations that led to their definition. In the following, some of the original considerations will be recalled and essential properties of the quantities will be discussed. However, no attempt will be made to retrace more recent arguments that led to the adoption of the quantities by the *ICRU* (1,2) or to the statements made by the *ICRP* on the index quantities (3,4).

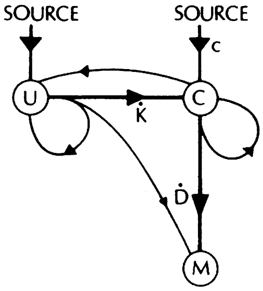
Some additional remarks will deal with a quantity for radiation protection monitoring that is closely related to the effective dose equivalent and that is also in an interesting relation to the dose-equivalent index. This is a contribution to the current discussion and reflects no official position.

Need for a Receptor Related Field Quantity

The concepts of absorbed-dose index and dose-equivalent index originated in a news item and a subsequent discussion with *H.H.Rossi*. The item in the news had been the statement that two US astronauts had traversed the Van Allen belt at a period of increased radiation activity, and that during this period the *dose rate* expressed in rads per hour was alarmingly high. The subsequent discussion arose from the obvious question whether such a statement had traceable quantitative meaning. It was readily apparent that it had not. The statement of an absorbed-dose rate - particularly in an unknown radiation field - can be meaningful only if the receptor conditions are defined. If the receptor conditions are not specified, values of absorbed dose or of absorbed-dose rate may say very little. The situation in space, complicated by the presence of a magnetic field and by an unknown degree of secondary charged particle equilibrium, was an evident example for the desirability of a dose quantity that could be meaningful even in arbitrary and unknown radiation fields.

Kerma or kerma rate would be a suitable quantity if one dealt merely with uncharged radiations. It offers a convenient way to disregard the complexities of energy transport by secondary charged particles, and in those usual cases where the absorbed-dose concept is unproblematical kerma tends to be numerically equal to absorbed dose. If one dealt merely with photon radiation or with fast neutrons, kerma would be an entirely adequate monitor quantity for protection. However, it is hardly satisfactory to restrict basic definitions to certain types of radiation, and the question arises, therefore, whether the concept of kerma or a related notion could be made applicable to general radiation fields.

Even a simplified graph of the complex pathways and loops of energy transport between uncharged radiation fields, charged



Schematic diagramme of the different channels of energy flow between the uncharged radiation field, U, the charged radiation field, C, and the irradiated matter, M.

The symbols $\dot{K}$ and $\dot{D}$ indicate those terms that contribute to the kerma rate and the absorbed-dose rate.

radiation fields, and matter serves to indicate that there is no simple extension of the kerma concept.

Kerma rate,$\dot{K}$,is defined in terms of the energy flow rate from the uncharged radiation field,U, to the charged radiation field,C. The uncharged radiation field,U, remains essentially unchanged if a small receptor is introduced and kerma is therefore meaningful without exact specification of the receptor geometry.

In contrast, the charged particle field depends strongly on the receptor geometry. Accordingly there is no simple approximation for absorbed-dose rate in those cases where there is, in addition to $\dot{K}$, a source term,c, for primary charged ionizing particles. An explicit specification of the receptor geometry is therefore required if one wishes to avoid potentially complex postulates such as the attainment of charged particle equilibrium. It was therefore natural to define a field quantity for receptor free conditions that is nevertheless related to a suitably chosen standard receptor.

A field quantity in the usual sense is defined on points and refers to properties of the radiation field at these points. Such quantities may, accordingly, be inadequate to specify energy deposition in an extended body that is centered at the reference point. However, one can understand the concept of a field quantity in a broader sense. Its value at a point can, in this wider definition, depend also on properties of the radiation field within a certain neighbourhood of the reference point. This led to the adoption of a highly simplified phantom, the 30cm diameter tissue equivalent sphere. Furthermore it was natural to choose the center of the sphere as reference point.

It is important to note that introducing the sphere into the definition of a field quantity is one essential step, while the actual dependence of the quantity on the dose distribution within the sphere is a second and separate problem.

In the definition of the index quantities one particular convention has been chosen, and the reasons for this choice will be dealt with in the following section. A subsequent section is concerned with an alternative convention and shows that additional quantities may be obtained that are also of potential interest to radiation protection.

Definition in Terms of the Dose-Equivalent Maximum and Some Consequences

When the index quantities were first considered dose equivalent was merely related to specified points within critical tissues or organs in the exposed body. The most straightforward interpretation of the dose-equivalent limits was therefore in terms of the maximum dose equivalent occurring in the human body. Accordingly the absorbed-dose index and the dose-equivalent index were also defined in terms of maximum values within the sphere. Fine details, such as the skin of the sphere or the different layers of the sphere, need not be dealt with in the present discussion that is aimed at the basic arguments.

The definition in terms of the maximum confers upon the index quantities certain unfamiliar properties. One of these particularities, the reference to a point with simultaneous dependence on field properties in an extended region, has been discussed.

A further somewhat unfamiliar property is the dependence on angular distribution of fluence. It is sometimes assumed that a single valued field quantity should be dependent only on total fluence and not on its angular distribution, but this is by no means a necessary requirement. At a specified total fluence a unidirectional radiation may well cause a larger risk than the isotropic field, and it is therefore not inappropriate that the index quantities are larger for the unidirectional field.

The frequent objection that the index quantities can not be *measured*, or can not be *measured directly* appears to be fallacious. The same argument has, on occasions, been applied against numerous other quantities. In fact, no physical quantity is ever *measured directly*; the process of measurement is by its very nature an often complex chain of interactions, transformations, and inferences.

One can certainly raise the practical objection that it is easier to construct detectors that are *additive*, in the sense that they sum the response to various components of a radiation field. However, one must note that this objection is based on practical considerations, not on principal requirements.

Lack of *additivity* in a temporal sense is another particularity of the index quantities. It has been frequently commented upon and deserves consideration.

Let $H_I(t_1,t)$ be the dose-equivalence index for the time interval t_1 to t, and let t_2 be a time between t_1 and t. Then one has the inequation:

$$H_I(t_1,t) \leqq H_I(t_1,t_2) + H_I(t_2,t) \qquad (1)$$

The equality applies for *stable fields*, i.e., for fields that may change in intensity but are otherwise constant.

What is usually termed lack of additivity, can also be described as the lack of a unique value of the time derivative of the index quantities. At a specified location and time, t, index rates can be different in a field that is not stable:

$$\dot{H}_I(t_1,t) \neq \dot{H}_I(t_2,t) \qquad (2)$$

Nevertheless there can be a rate meter for the index. Such an instrument would measure the quantity:

$$\dot{I}(t) = \dot{H}(t,t) \qquad (3)$$

that is equal to the maximum of the dose-equivalent rate in the sphere. $\dot{I}(t)$ can be called the dose-equivalent-rate index; for stable fields it is equal to the rate of change of the dose-equivalent index. In general it is merely an upper bound and its integral is an upper bound for the dose-equivalent index:

$$\dot{H}_I(t_1,t) \leq \dot{I}(t) \quad \text{and} \quad H_I(t_1,t) \leq I(t_1,t) = \int_{t_1}^{t} \dot{I}(\tau)\, d\tau \qquad (4)$$

The equality applies in stable fields.

In passing, one may note that the quantity I is intermediate in character between H_I and the dose-equivalent ceiling (5) which is an even more conservative quantity, particularly suitable for uncharged radiations.

The unfamiliar properties expressed in Eqs(1-4) indicate that the index quantities are primarily intended for routine monitoring rather than for quantitative book-keeping purposes.

It is not too surprising, in view of Eqs(1-4), that doubts have been expressed as to the consistency of the underlying definitions. Such doubts can be dispersed by a simple example. Assume that $H(t_1,t)$ is the distance, at time t, of a moving point from its location at time t_1. This entirely innocuous function will also obey Eqs(1-4), and the reader will find it easy to interpret the terms $\dot{H}(t_1,t)$, $\dot{I}(t)$, and $I(t_1,t)$.

Consideration of a Related Quantity

As stated, the definition of the index quantities is linked to the maximum of the dose equivalent or of the absorbed dose in the simplified phantom. This concept is sufficient in the common situation where exposures are too low to merit quantitative assessment. The field monitor quantity $\dot{I}$ serves then to ascertain normal, low levels of radiation that necessitate no book-keeping of time spent by individuals at the specified location.

The more recent philosophy of ICRP is largely oriented towards a cost-benefit balance in radiation protection. The introduction of the *effective dose equivalent* to a human body from internal emitters and the extension of this concept to external irradiation is in line with this development.

One may therefore ask for a field quantity, tentatively called Ω, that is related to the effective dose equivalent and that is also based on the tissue equivalent standard sphere. It is evident that such a quantity is not identical with the effective dose equivalent in a particular human body after a particular exposure. Nevertheless, a definition can be sought that makes Ω or its rate a meaningful *estimator* of the effective dose equivalent or its rate in the body of a person at the specified location. It need not be emphasized that such a quantity could, in many cases, be utilized instead of the effective dose equivalent; but it is equally evident that in critical situations the actual value of the effective dose equivalent will have to be inferred from a more thorough investigation or from appropriate personal dosimeters.

As with the index quantities, the definition of the quantity Ω is related to the 30cm tissue sphere, but it requires the choice of a response function that depends on distance from the center of the sphere. The dose equivalent or dose-equivalent rate in the sphere must be weighted by this response function.

The precise form of the response function that would lead to the best estimate may deserve further investigation; however, it could turn out that a constant function is acceptable and that, consequently, the average dose equivalent or its rate in the sphere is a suitable estimator for the effective dose equivalent or its rate in a human body of unspecified orientation, size, sex, or age at the specified location.

Concluding Remarks

There is a need for field quantities that preserve their meaning even in arbitrary and unknown radiation fields and that can be utilized for radiation protection monitoring. The dose-equivalent index and the dose-equivalent-rate index are such quantities; they are related to the concept of the maximum dose equivalent in the human body.

The introduction of the index quantities involved two distinct steps that need not necessarily be coupled. The first step is the choice of a greatly simplified phantom, the 30cm tissue equivalent sphere. The second step is the definition in terms of the maximum of absorbed dose or dose equivalent in the sphere; it makes the quantities applicable to those common conditions where ceiling values are sufficient.

Whenever a more precise assessment of exposures is desirable the concept of a maximum of the dose equivalent in the human body may be impractical. The effective dose equivalent may then be invoked. In critical situations this quantity can be assessed by detailed computations or measurements that account for the particularities of a human body, its location, and orientation during exposure. It can also be estimated from personal dosimeters that are suitably calibrated and appropriately worn by the supervised person. In less critical situations a monitor quantity, Ω, could be used that serves as estimator of the effective dose equivalent or its rate in a human body at the specified location. Ω shares with the index quantities the property of being a point quantity dependent on the dose distribution in a tissue equivalent sphere. However, the definition of the quantity involves an averaging of dose equivalent within the sphere.

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