Rigour Within Uncertainty

The Need for a Strict Definition of the Quality Factor

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Dual Purpose of Radiation Protection Quantities

Quantities for radiation protection serve a double purpose. They are used as indicators of the potential harm produced by a radiation exposure, and they are employed as reference parameters in rules and regulations for radiation protection. A few years ago H.H.Rossi distinguished between two applications by speaking of the assessment system and the limitation system.

The limitation system used to be the basis of radiation protection: dose limits were introduced that appeared to be practicable and entirely safe. When it was realized that stochastic radiation effects can be produced with small but non-zero probability even by low doses, the assessment system was introduced. Its primary principle is to reduce exposures to levels of acceptable risk. To judge the acceptability of risks, one needs to know their magnitude, but the risk estimates are subject to considerable uncertainty. Within the assessment system there is, accordingly, no point in asking for precision in dose determinations.

However, the assessment system cannot stand by itself. To keep exposures as low as reasonably achievable is the primary aim of radiation protection. But to enforce rules and regulations one needs also formal principles that permit an objective and quantifiable distinction between the permissible and the unacceptable. The limitation system must, therefore, complement the assessment system, and it requires accuracy and precision in dose determinations. The magnitude of the limits that are adopted in radiation protection is largely arbitrary, but once a value is adopted, it needs to be compared to measured or computed doses and there is a need for precise instrument calibrations. In a formal system, precision is required, even in the face of uncertainty.

The work of the two International Radiological Commissions reflects the two complementary aspects of radiation protection. Where there is complementarity, there is always the appearance, and sometimes the actual danger, of incongruity. The revision of the quality factor in radiation protection exemplifies this dilemma.

Revision of the Quality Factor

New radiobiological findings suggest a higher relative efficiency of densely ionizing radiations, and especially of neutrons, in comparison to γ rays or x rays, than had previously been assumed. This indicates the need for a revised quality factor. These matters have been treated in ICRU Report 40, *The Quality Factor in Radiation Protection*, and more recently they have also been considered in the preparation of the new recommendations of the ICRP. There is considerable latitude in the choice of the numerical values of the quality factor, and any new convention that is in reasonable agreement with radiobiological data is, therefore, acceptable. Within the framework of the assessment system and in view of the uncertain risk estimates there is, as ICRP notes, no need for detail and precision, and this suggests the simplest possible approach to the definition of the quality factor.

Within the limitation system, simplicity is equally desirable, but it cannot be attained by a loss of rigour. ICRU prefaces its most recent summary of "Quantities and Units for Use in Radiation Protection" by the statement:

> *Quantities relevant to radiation protection must often be used with a variety of approximations. Although a comparatively wide margin for numerical uncertainties may be admissible in radiation protection, it is essential that the quantities employed be clearly defined, and the approximations clearly identified.*

The definition of the quality factor and possible ramifications of the concept need to be examined under this premise.

Considerations on the Definition of the Quality Factor

The Conventional Approach

The current convention is based on the familiar concept of the quality factor as a function of the linear energy transfer (L), and a revision may merely replace the current convention $Q(L)$ by a changed numerical relation. This is a matter of taking into account new radiobiological information, it does not change the concept. The approach remains consistent.

The quality factor, Q, and the dose equivalent, H, at a point:

$$Q = \int Q(L)\, d(L)\, dL$$

$$H = Q \cdot D$$

are utilized to compute the dose equivalent, H_T, in an organ,T, or "the (mean) quality factor", Q_T, for the organ:

$$H_T = \int_{m_T} Q \cdot D\, dm \quad (m_T : \text{mass of the organ})$$

$$Q_T = \int_{m_T} Q \cdot D\, dm \,/ \int_{m_T} D\, dm$$

$$= H_T \,/\, D_T$$

The derivation of H_T or Q_T involves a double integration over the distribution, d(L), of dose (at the point) in LET and over the tissue of interest. This can be complex, but it is not, in principle, much more difficult than the computation of the organ absorbed dose, D_T.

In most instances, it is, of course, unnecessary to perform the exact computations. Instead one can use approximations, such as the conventional values 10 and 20 for neutrons and α particles. The wide applicability of approximations can, however, not remove the need for precise definitions, as they are required in standardization and calibration procedures.

The actual dependence for the organ dose equivalent or for the "effective dose":

$$H_e = \sum_T Q_T\, w_T\, D_T$$

can, of course, be replaced by an approximation. For example one can write:

$$H_e = \overline{Q} \sum_T w_T\, D_T$$

where $\overline{Q}$ is not obtained by the actual integration over the organs, but is an approximation for the mean quality factor of the radiation.

In principle, however, Q_T depends on the organ and, apart from the energy distribution of the radiation, also on its directional distribution.

In summary: one can use the familiar system of the quality factor, $Q(L)$, defined in terms of the parameter L. This does not exclude the recommendation of approximations that disregard the dependence of the quality factor on organs and on the directional distribution of the radiation (or position of the body).

The combination of an exact definition with the use of acceptable approximations for typical radiations has been proposed in ICRU Report 40, *The Quality Factor in Radiation Protection* by a liaison committee of ICRU and ICRP.

Reasons for Seeking a Simpler System

While the conventional system is, in itself, coherent and while it has worked sufficiently well in the past, a simplified approach is now considered. It aims at the introduction of a "receptor free" quality factor, i.e., it postulates that the quality factor depends only on the characteristics of a radiation field, without the need to consider the modified field that occurs when the human body is actually present.

The simplification appears attractive, but whenever one computes effective doses, it leads to a certain incongruity: the simplified quality factor that disregards the specific characteristics of the exposed body is combined with the complexity of computing actual absorbed doses within the different organs.

There are, of course, good reasons for seeking the simpler system. Computations of *absorbed dose* can be complex, but they pose no problems in principle. For a specified radiation field and a specific orientation of the body (or phantom) one obtains results that will remain valid. Computations of *dose equivalents*, on the other hand, are less permanent. New epidemiological findings or radiobiological results may, in the future, lead to changed conventions on the quality factors.

This lack of permanence suggests:

- That there is little justification for detailed or accurate conventions on the quality factor.

- That it is desirable to "uncouple" the computation of the organ (absorbed) doses, D_T, and their weighted sum, $w_T D_T$, from the further step that accounts for radiation quality. The uncoupling would obviate the need to perform the full computations *de novo* for any assumed or newly introduced set of quality factors.

These two aspects are, in fact, strong support for the idea to utilize "receptor free" quality factors that depend only on the type and energy of the ionizing radiation. The approach appears, therefore, attractive. Unfortunately, it leads to inconsistencies that make it usable only as an approximation.

The Simplified Approach

In the subsequent consideration of the simplified approach, we will use the term "radiation weighting factor" rather than the familiar term "quality factor". This reflects merely the terminology chosen in preliminary discussions by ICRP. The notation is irrelevant to the essence of the discussion, it is adopted for the present considerations, and it should not be seen as support for a changed terminology.

It has been recommended that the radiation weighting factors be defined in a receptor free way, so that they will depend only on the type and energy of the radiation but not on the organ and the orientation of the body or the directional distribution of the field.

In a receptor free definition, it is natural to abandon the LET as the reference parameter and to use instead of $Q(L)$ a convention that links the weight, $w_R(E)$, to the energy, E, of a radiation (R) of specified type (e.g., neutrons).

Instead of a continuous dependence, $w_R(E)$, a simple step function, i.e., only a few discrete values for certain energy bands, have been considered. This is analogous to the initial convention on $Q(L)$ which had also been formulated in terms of discrete values for a few bands of LET-values. To choose between a continuous or discontinuous function $w_R(E)$ is a secondary matter. We will, in the following, consider the simplified approach in terms of discrete values, w_R, for a number of energy bins of a specified radiation, e.g., neutrons. It would be straightforward to translate the formulae to the continuous case. Assume that one deals with one "type of radiation" (monoenergetic neutrons or neutrons in the same energy bin), the dose equivalent in an organ T is then:

$$H_T = w_R \cdot D_T$$

and the effective dose is:

$$H_e = \sum_T w_R \cdot w_T D_T = w_R \cdot D_e ,$$

where D_e may be termed the "effective absorbed dose".

Clearly the "organ radiation weighting factor", H_R/D_R, and the "effective radiation weighting factor", H_e/D_e, are equal to the value w_R, and this is in line with the simplified procedure.

But the seeming simplicity disappears for an actual radiation field, e.g., a neutron field that consists of several energy bins. The simplified approach would suggest that the overall radiation weighting factor, w_r, of the field, i.e., the ratio of the organ dose equivalent, H_T, and the organ (mean) absorbed dose, D_T, be organ independent. But the formulae do not confirm this expectation. From:

$$H_T = \sum_R w_R D_{T,R}$$

and

$$D_T = \sum_R D_{T,R}$$

one obtains:

$$w_r = H_T / D_T = \sum_R w_R D_{T,R} / D_T$$

and this is, by no means, organ independent.

Numerical examples show that the differences between the values w_r for different organs can be large. For a frontal exposure to fission neutrons with accompanying γ rays, a large value w_r will result for the breast, but a considerably smaller value for the bone marrow where the γ rays may predominate.

The appealing simplicity of the approach is thus lost whenever one deals with mixed radiations. There is no radiation weighting factor for a mixed field, and there is, accordingly, no direct way from the organ absorbed dose to the dose equivalent. Mixed radiations are, however, the usual condition in radiation protection.

One may seek a way out of the dilemma. An earlier discussion of the problem led to the recommendation of a "receptor free" radiation factor for a mixed radiation:

$$w_r = \sum_R w_R D_R^* / D^*$$

where D_R^* the contribution of the different radiation types to the ambient absorbed dose, D^*. Alternatively, one could, of course, sum over some other receptor free quantity, such as kerma.

The added convention would reestablish the desired simplicity, and as an approximation it would certainly be adequate. As part of a rigorous definition it introduces, however, a deeper inconsistency. The definition

$$H_T = w_r \cdot D_T$$

provides a value of H_T that differs from the sum of the organ dose equivalents due to the component radiations ("radiation types"),

$$H_T = \sum_R w_R \cdot H_{T,R}$$

The same problem would, of course, arise for the effective dose.

There is an unwelcome conclusion from these considerations. Either there is organ dependence of the radiation weighting factors of a real field, or the added convention causes the effective dose to be different from the sum of the effective doses due to the component radiations. Either conclusion is sufficiently unpalatable to make the simplified radiation weighting factors an unattractive tool for basic definitions.

ICRU is, of course, not merely concerned with rigour in the definition of quantities. An equal concern is practicability, and this, too, may argue against the "simplified" definition of the quality factor. To use energy of the ionizing radiation as the reference parameter would tend to replace the comparatively straightforward measurements of LET distributions - or rather of *y* distributions - by more difficult determinations of the fluence spectra in energy. This would turn the intended simplicity into its opposite and produce needless complications.

Conclusion

The practice of radiation protection can usually be based on simplifications and approximations. The present discussion may, therefore, appear as a fancy way to make plain things complicated. Conceptual clarity is, on the other hand, an essential ingredient of simplicity, and simplicity must not be confused with looseness or with the approximations that are admissible under many circumstances. The rigour of the underlying definitions may not become apparent in many applications of radiation protection quantities, but it is the necessary skeleton that supports the system of radiation-protection measurements, computations and calibrations and that avoids conflicts of interpretation and needless discussions.

Confusion in the basic definitions can never be a fair price for simplicity. But rigorous definitions do not exclude the use of approximations, if they are recognized as such.