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Quality Factor for Low Doses of High-LET Radiations

Werner Hofmann
University of Salzburg

Robert Katz
University of Nebraska - Lincoln, rkatz2@unl.edu

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LETTERS TO THE EDITORS

Quality Factor for Low Doses of High-LET Radiations

Dear Sirs:

The International Commission on Radiological Protection (ICRP77) and the International Commision on Radiation Units and Measurements (ICRU70) have recommended that the evaluation of radiation hazards be based on the "dose equivalent" defined as the product of the absorbed dose and some modifying factors, the most important of which is the quality factor (Q). The quality factor is intended to allow for the effect on the resulting detriment of the microscopic distribution of the absorbed energy. It is therefore defined as a function of the collision stopping power (L_∞) in water at the point of interest. Thus Q rises monotonically with increasing LET until 175 keV/μm where it achieves a value of 20 and remains at 20 for all higher values of LET.

These high Q values for very high LET radiations are exactly the point we want to focus on in this letter.

Though ICRP (ICRP77) issues a cautionary note that the assigned values of Q are not necessarily representative values of the relative biological effectiveness (RBE), say for stochastic effects at low dose levels, such high Q values are completely misleading for all biological endpoints for which the survival of the affected cell is indispensible. Since cancer induction represents the most important radiation hazard at low doses, the following arguments are specifically directed to this problem.

We assume that malignant transformation is a necessary condition for cancer induction. We further assume that dose and dose rate are so low as to allow complete repopulation of all killed cells, so that the function in the irradiated tissue is restored. Thus malignant transformation and subsequent cancer initiation present no hazard unless the affected cells survive. At 170 keV/μm a cell whose nucleus is threaded by a heavy ion has a probability of survival of about 0.4. At 500 keV/μm this probability is reduced to about 0.016, and at 1000 keV/μm it is reduced to about 10^{-4}. These numbers are calculated from the radiosensitivity parameters for T-1 kidney cells (m = 2.5 and κ = 1000) using the expression for the probability of cell killing given by track theory as $P = (1 - e^{-z^{*2}/\kappa\beta^2})^m$. Here z^* is the effective charge number of the ion and β is its speed relative to light. The relation between LET and z^{*2}/β^2 is shown in Figure 1. While our calculations are for kidney cells, the parameters of other mammalian cells lie nearby, with m being between 2 and 3 while κ lies between 500 and 1500 (Roth 1973). Thus different radiosensitivity parameters more suitable for other mammalian cell lines would not change essentially the above-calculated survival probabilities or the implications of these calculations.

Track structure calculations have clearly demonstrated that for sufficiently high LET values every cell whose nucleus is traversed by a charged ion is killed. We wish therefore to suggest that an effective quality factor Q_{eff} be defined as the product of an ICRU/ICRP factor and the survival probability S, where

$$S = 1 - (1 - e^{-z^{*2}/\kappa\beta^2})^m. \tag{1}$$

The form of the factor suggested by ICRP 77 increases to a value of 20 at 175 keV/μm, and remains level at that value for higher values of LET, as plotted in Figure 2 as Q_{ICRP}. An additional form suggested by ICRU 70 is stated functionally as

$$Q_{\text{ICRU}} = 0.8 + 0.16\, L_\infty\ \mu\text{m/keV}. \tag{2}$$

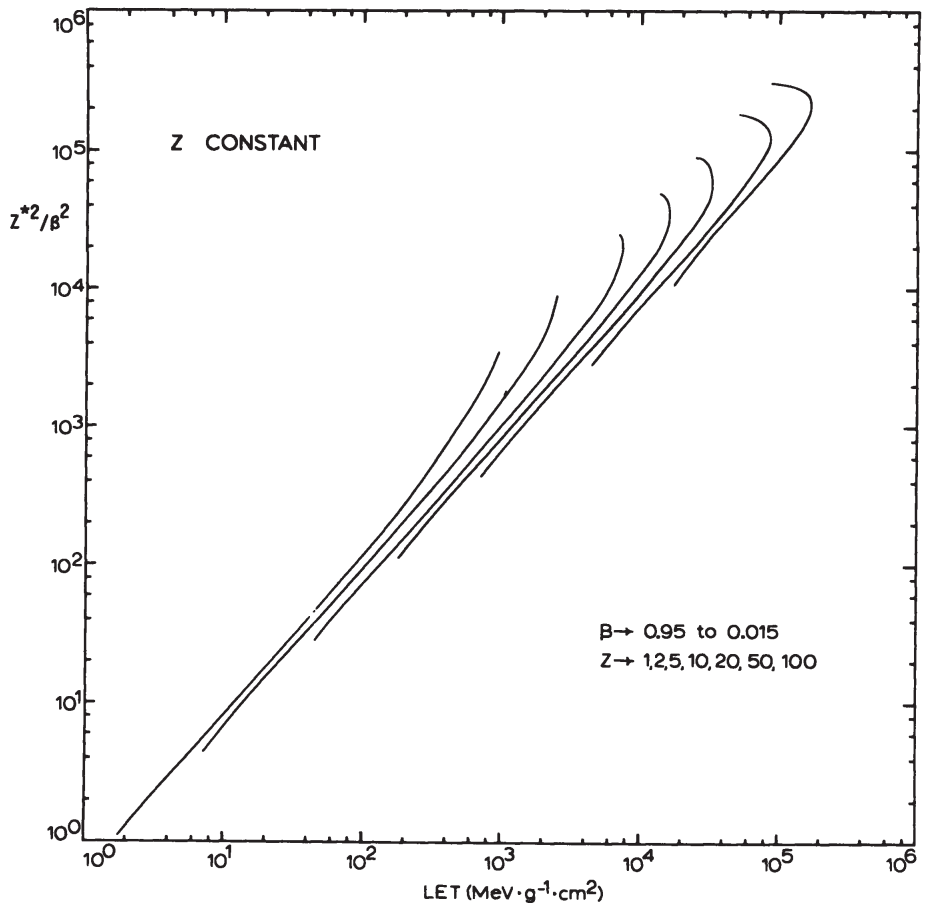

Figure 1. The fact that z^{*2}/β^2 is not a single valued function of LET implies that the response of biological cells to ionizing radiation cannot be represented as a single valued function of LET. The individual curves giving z^{*2}/β^2 as a function of LET are plotted for single values of the atomic number Z, being 1 at left and 100 at right, and for values of β from 0.95 leftmost and lowest (of any one curve) and 0.015 at the highest end.

In Figure 2, we have drawn graphs representing the products $Q_{ICRU} \times S$ and $Q_{ICRP} \times S$. We suggest in practice it would be more convenient to make use of an analytic expression for Q_{eff} and nominate, as an effective value of the quality factor, the form

$$Q_{eff} = Q_{ICRU} \times S. \tag{3}$$

For our calculations we have used a representative relation between LET and z^{*2}/β^2 by setting the two to be numerically equal when LET is expressed in MeV/cm, in water.

The newly defined effective quality factor Q_{eff} tends to zero at very high LET. This may be of importance for the potential carcinogenic action of neutron irradiation, since all heavy secondaries, e.g. C, N, and O nuclei have LET values at which every cell whose nucleus is intersected is killed. What we propose is a step beyond the

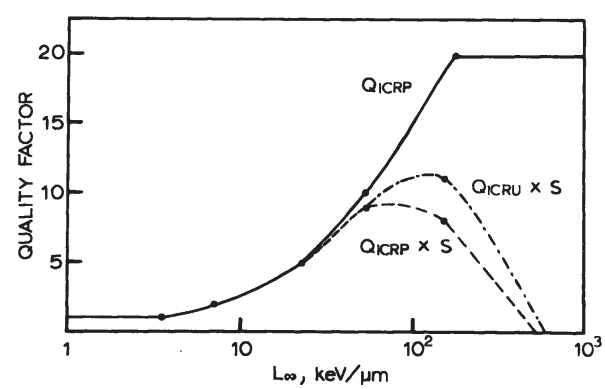

Figure 2. (a) Q_{ICRP}, the form of the quality factor recommended in ICRP 77. **(b)** $Q_{eff} = Q_{ICRU} \times S$. **(c)** $Q_{ICRP} \times S$. For these calculations we have used radiosensitivity parameters for T-1 kidney cells and have approximated z^{*2}/β^2 as equal to the numerical value of LET when expressed in MeV/cm, in water.

decision of ICRP to truncate the ICRU quality factor at 20 to take cell killing into account. Our Equation 3 suggests also a smaller quality factor for alpha particles of about 10 instead of 20, a value already used in earlier regulations.

Stated here only for radiation induced carcinogenesis, the same argument can be applied to all biological endpoints which occur only in surviving cells, and also to higher doses as long as tissue damage can be completely restored or does not interfere with the effect under consideration.

Werner Hofmann
Division of Biophysics
University of Salzburg
A-5020 Salzburg, Austria

Robert Katz
University of Nebraska–Lincoln
Lincoln, NE 68588

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