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THE QUALITY FACTOR FOR NEUTRONS IN RADIATION PROTECTION: PHYSICAL PARAMETERS

A. M. Kellerer and K. Hahn
Institut für Medizinische Strahlenkunde der Universität Würzburg
Versbacher Straße 5, D-8700 Würzburg, FRG

INVITED PAPER

Abstract — Recommendations by NCRP and ICRP for a selective increase of the quality factor for neutrons have not been implemented in the practice of radiation protection, but have added urgency to the search for a more consistent new convention on quality factors. In response to this need, a liaison group of ICRP and ICRU has proposed numerical changes, but also a replacement of the reference parameter LET by the microdosimetric variable lineal energy. This would make quality factors and dose equivalents measurable, but would make computations more complicated. To resolve the dilemma, it is proposed to use an equivalence relation between lineal energy and LET which leads to nearly identical definitions whenever one deals with charged particles of sufficiently long range. For photons below 200 keV and for neutrons below 0.5 MeV, the equivalence is imperfect, but it may, even in these cases, be acceptable for the practical purposes of radiation protection.

INTRODUCTION

There has been increasing evidence in recent years that dose equivalents of densely and sparsely ionising radiations are not equivalent, but that those of densely ionising radiations are substantially more deleterious. NCRP and ICRP have considered the imbalance sufficiently serious to propose, in 1980 and 1986, that quality factors for neutrons be selectively increased by a factor of 2. The proposal has not been retracted by ICRP, and it has been re-affirmed in recent recommendations of NCRP[1]. That it has not been introduced into the practice of radiation protection may reflect dissatisfaction with an only partial and, from a physics standpoint, even illogical convention which departs from the adopted relation between the quality factor and the linear energy transfer merely in the special case when charged particles are set in motion by neutrons. The continued pressure for clarification prompted a liaison group of ICRP and ICRU to seek better solutions. The resulting recommendations[2] emphasise the need for a revision, but introduce a new dilemma by suggesting that the microdosimetric variable lineal energy, y, replace the accustomed parameter LET in the definition of the quality factor. This is a controversial issue that may delay a new convention or even perpetuate the present impasse. It is, therefore, necessary to reconsider the situation.

A definition in terms of lineal energy is desirable, because it permits the determination of quality factors in unknown radiation fields. A definition in terms of LET is advantageous, because it facilitates computations and satisfies conservatism in radiation protection. The difficulty of an arbitrary and unsatisfactory choice can be resolved, if equivalent definitions of the quality factor can be given in terms of lineal energy and LET.

Before dealing with details of a revised definition one must address a familiar argument against any change of quality factors. According to this argument, current risk estimates for sparsely ionising radiations are so overly conservative that any change of quality factors for densely ionising radiations would be pointless, even in the face of high values of RBE. To examine the validity of this argument one needs to consider the data from Hiroshima and Nagasaki after the revision of the atomic bomb dosimetry[3].

Figure 1 gives the relative risks derived by Preston and Pierce[4] for cancer mortality (except leukaemia) up to the year 1985. According to the revised dosimetry neutrons play only a minor role; the results therefore reflect essentially the effects of γ rays. Assuming a total cancer mortality of 18% in the population one obtains the absolute risks indicated on the right ordinate. The lower, straight line refers to this ordinate, and represents the current risk estimate 0.01 Sv^{-1} for non-leukaemia cancer mortality[5]. A minor part of the difference between the two dependences is due to the fact that the ICRP estimates are related to a working age population, while the Japanese data refer to the total life-time study sample which includes younger as well as older cohorts. For the younger cohorts the projection of observed relative risks throughout life could over-estimate the absolute risk factors. However, one finds that any resulting corrections are far less than the difference between the dependences in Figure 1, and it is, therefore, evident that current risk estimates contain a substantial reduction factor for the extrapolation from large to small doses or dose rates. While any risk estimates for small doses remain tentative, one has, apart from unproven biological hypotheses, no basis for the statement that present risk estimates are overly conservative. They may, in fact, need to be raised.

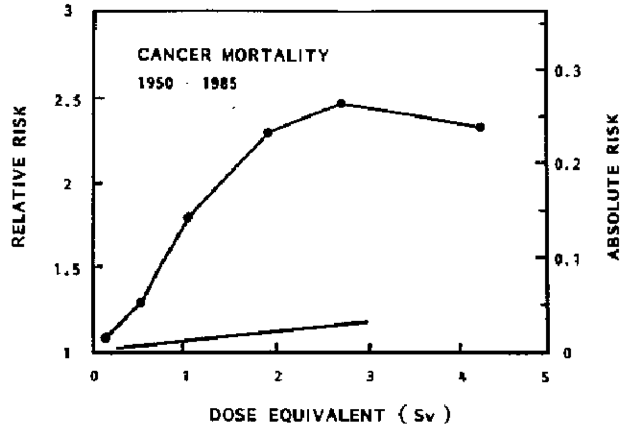

Figure 1. Relative risk of cancer mortality without leukaemia for the life-time study sample of atomic bomb survivors in Hiroshima and Nagasaki, up to 1985[4]. The right ordinate gives the absolute risks that apply, if the relative risks persist throughout life and if cancer is assumed to contribute 18% to total mortality. The straight line represents the risk estimate of 0.01 Sv^{-1} by ICRP[5] for cancer mortality (without leukaemia) in a population of working age.

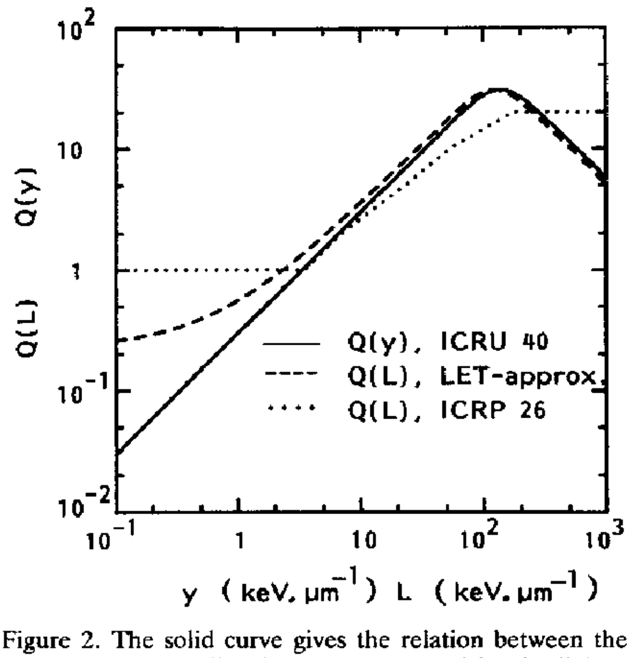

Figure 2. The solid curve gives the relation between the quality factor and lineal energy, proposed by the liaison group of ICRP and ICRU[2]. The broken curve represents the corresponding relation between the quality factor and LET (see Equation 3). The current definition of the quality factor, as a function of LET, is represented by the dotted curve.

THE PROPOSED REVISION OF THE QUALITY FACTOR

The liaison group of ICRP and ICRU has proposed a revised quality factor linked to the reference parameter lineal energy, rather than LET. The solid curve in Figure 2 represents the relation. Lineal energy, y, is a close analogue of LET; unlike LET it reflects actual energy depositions in microscopic sites. The distribution of y can be measured in an unknown radiation field, while measurements of LET require various approximations. However, a definition in terms of y is limited, too, as there are, at present, no methods of measurement in very small regions. The liaison group has, therefore, proposed a reference region of 1 μm diameter, which is in essential agreement with the present usage of total, rather than restricted, LET.

An analytical expression proposed by the liaison group has the drawback, that it does not correspond well to the intended proportionality of Q and y at small values of y. It is, therefore, better to use the following analytical expression which avoids the disadvantage and is in equal agreement with the solid curve in Figure 2:

$$Q(y) = 0.3\, y\, [1 + (y/137)^5]^{-0.4} \qquad (1)$$

where

y is in keV.μm^{-1}. The subsequent considerations apply to this definition, but will remain valid if different numerical values are chosen in an impending new convention on the quality factor.

AN EQUIVALENT DEFINITION IN TERMS OF LET

While lineal energy is measureable, the linear energy transfer has the advantage that its distribution can be more readily computed for a known radiation field. Depending on circumstances, one may therefore prefer a definition in terms of lineal energy or one in terms of LET.

For densely ionising charged particles of sufficient range the correlation is simple:

$$\bar{y}_D = \frac{9}{8} L \qquad (2)$$

The factor 9/8 reflects the variance of chord lengths in a sphere[6,7]. To give equivalent definitions in y and LET is then trivial. For electrons and relativistic protons such simple equivalence does not apply; for sparsely ionising particles the energy concentrations in microscopic regions can be predominantly determined by energy loss straggling, i.e. by individual δ rays. In an adequate approximation one can account for this influence of straggling by the formula

$$\bar{y}_D = \frac{9}{8}L + \frac{3\delta}{2d} \qquad (3)$$

where d is the site diameter. δ is the weighted energy mean imparted to the reference site by individual δ rays. The value δ = 500 eV is applicable to a site of 1 μm diameter[8].

Utilising the above formula one obtains the relation between the revised quality factor and unrestricted LET which is indicated by the broken line in Figure 2. For the pragmatic purposes of radiation protection, it will usually be adequate to employ the definition in terms of lineal energy when one deals with measurements, and to utilise the definition in terms of LET to simplify computations.

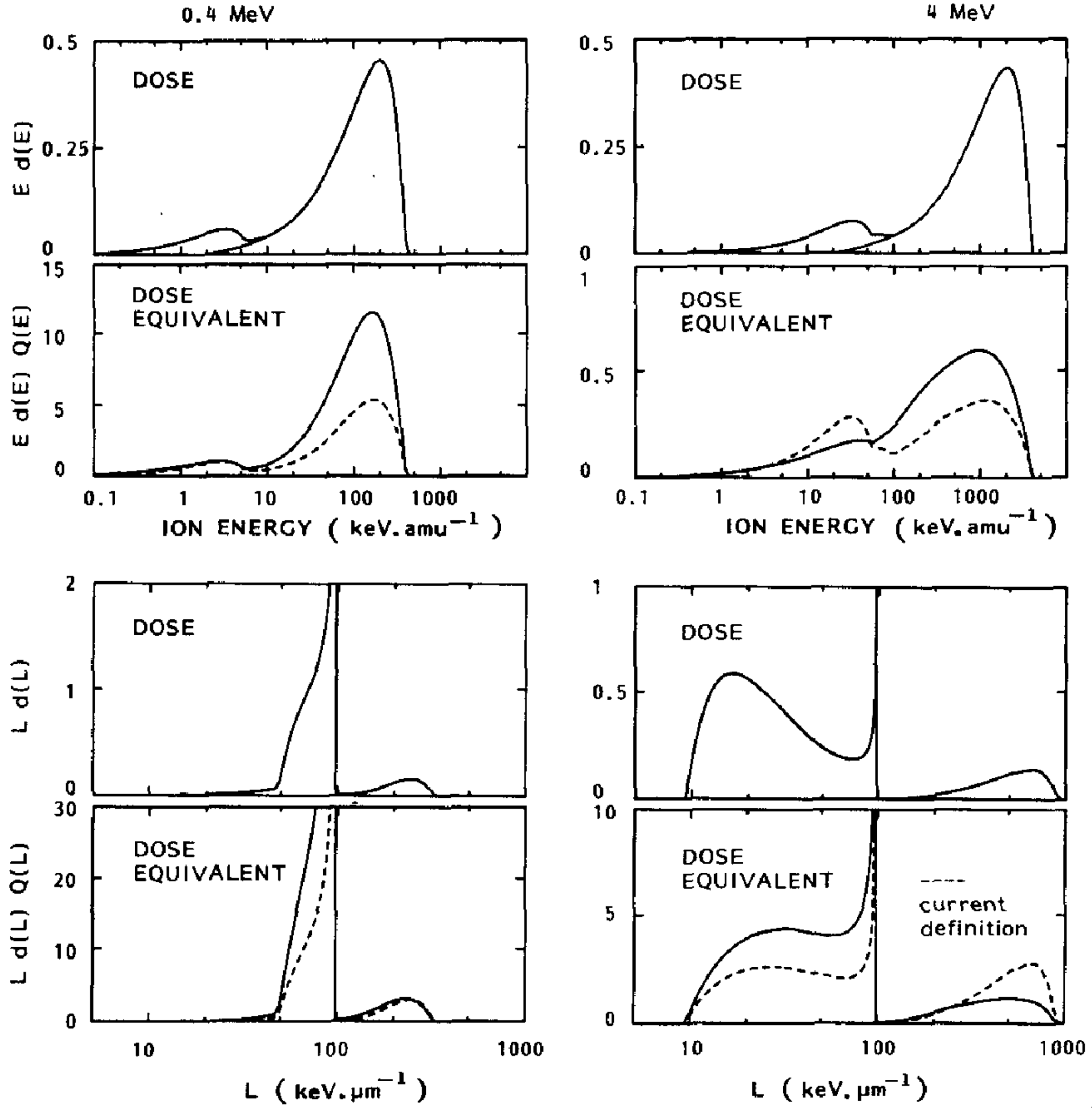

Figure 3. Distributions of dose and of dose equivalent in kinetic energy and unrestricted LET of the neutron recoils. The distributions are computed in terms of the continuous slowing down approximation for ICRU tissue and for the neutron energies 0.4 MeV and 4 MeV. The recoil energies are taken to be equally distributed and the total cross sections are those of ENDF/B-V[9]. For the dose equivalents the solid lines correspond to the revised definition in terms of LET (Equations 1 and 3); the broken lines correspond to the current definition of the quality factor.

The two definitions are nearly equivalent for particles with ranges much larger than 1 μm. However, deviations can occur for short range particles, i.e. for the recoils of soft X rays or of neutrons below 0.5 MeV. The magnitude of these deviations needs to be assessed by computations in terms of LET.

COMPARISON OF QUALITY FACTORS COMPUTED IN TERMS OF y AND LET

Quality factors for neutrons and photons have been given by the liaison group of ICRU and ICRP, and can be compared with results obtained in terms of LET. Computations in terms of LET are helpful also because they indicate the relative weight of different components of the charged particle spectrum in the current and the proposed definition of the quality factor.

Neutrons

Figure 3 gives, for two different neutron energies, the distributions, d(E) and d(L), of dose in the kinetic energy, E, and the LET, L, of the first generation recoil particles. It also gives the distributions of dose equivalent according to the current and the revised definition; these distributions are normalised to the quality factor, Q.

The contribution of the recoil protons to the dose equivalent is, in the revised definition, considerably enhanced; the role of the heavier recoils, with their substantially larger LET, is reduced.

At neutron energies of less than 0.5 MeV the ranges, even of the recoil protons, begin to be so short that the lineal energy is decreased because of incomplete traversals of the reference site and changing values of LET during the traversals. The definition in terms of LET leads, therefore, at low neutron energies to larger quality factors than the definition in terms of y. This is seen in Figure 4. The analogous effect for heavier recoil leads, at higher neutron energies, to a reversed change on the descending part of the defining relations in Figure 2. This explains why the computations in terms of LET yield somewhat lower values at high neutron energies.

Dose equivalent limits for neutrons can become critical if increased quality factors are introduced. The differences that result at neutron energies below 0.5 MeV may, therefore, not be entirely inconsequential, and the relation between the definitions of Q in terms of y and LET may, in this respect, need further consideration.

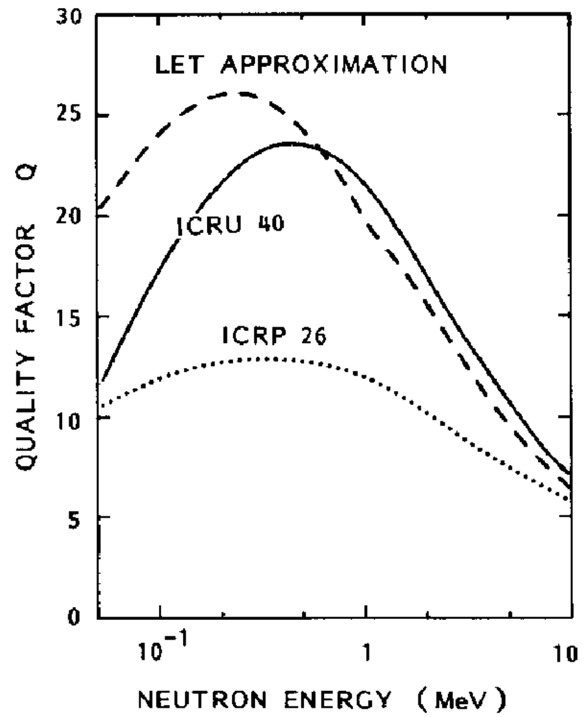

Figure 4. The solid curve gives the quality factor for monoenergetic neutrons according to the proposed dependence on lineal energy[2]. The broken curve results from the corresponding definition in terms of LET (see Equation 3). The dotted curve represents the quality factor in the current convention.

Photons

The problem of the quality factor for neutrons can not be separated from that of the reference radiation, and for this reason photons need also be considered. The liaison group of ICRP and ICRU has proposed conventional X rays as reference radiation, with a resulting value of approximately 0.5 for high energy photons. It is doubtful whether this convention will be adopted. Important data for risk estimates, such as the results in Figure 1, relate to γ rays. It also appears desirable that the reference radiation be sufficiently penetrating to include the important case of nearly uniform whole-body irradiation. Allowing for the likely modifications, it is nevertheless of interest to analyse the proposed quality factors for photons.

Figure 5 is largely analogous to Figure 3. It gives the distributions of dose and dose equivalent in the kinetic energy and the LET of the first generation photo and Compton electrons. There is no need for a comparison with the current definition of the quality factor which assigns the value 1 to electrons. On the other hand, one needs to note certain complications. First, it is necessary for electrons to utilise a cut-off. Computations in terms of unrestricted LET would disregard the appreciable fraction of the total fluence which is contributed by secondary electrons. This would lead to inconsistencies and inaccuracies. From the distributions of dose equivalent for 1 MeV photons the substantial contribution of the electrons in the range of a few keV is apparent. With no energy cut-off this contribution would be omitted. The broken lines in the distributions of dose equivalent indicate the results which would apply if the correction term for straggling in Equation 3 were omitted. The correction is essential for the low values of LET prevailing at high photon energies.

Figure 6 gives the overall comparison. It shows that one obtains, in terms of LET, substantially enhanced values for intermediate and low energy photons. As in the case of neutrons, this reflects the fact that actual energy concentrations in a 1 μm sphere are smaller than the LET value would indicate. The magnitude of the difference reflects the quantity of low energy Compton electrons released by photons of energy less than 200 keV.

CONCLUSION

The impending revision of the quality factors may

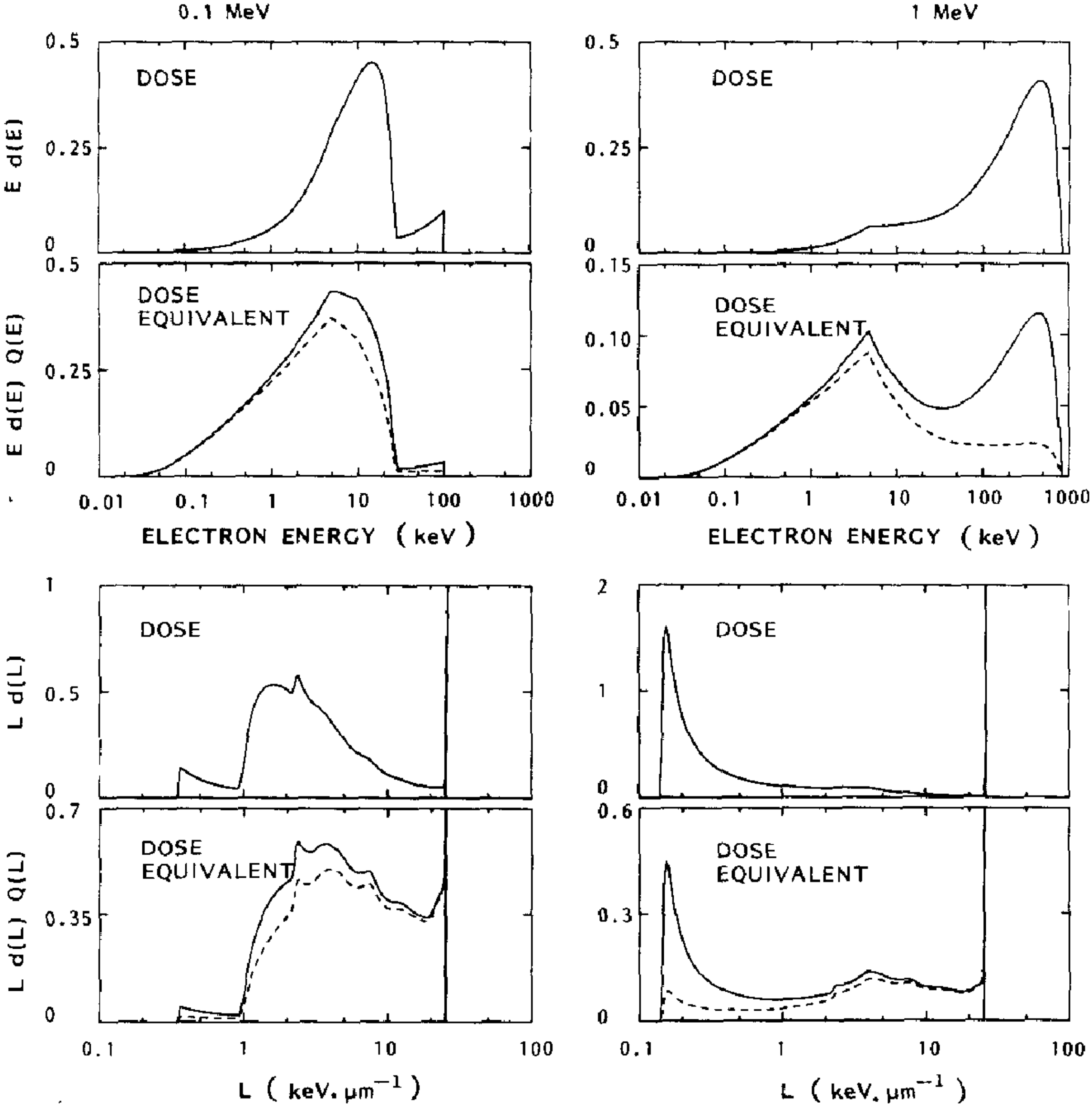

Figure 5. Distributions of dose and of dose equivalent in kinetic energy and LET (cut-off 5 keV) of the electrons released by monoenergetic photons in water. The distributions are computed for the photon energies 0.1 MeV and 1 MeV with an energy cut-off 5 keV and the continuous slowing down approximation. The broken lines represent the distributions of dose equivalent that result without the straggling correction in Equation 3; the solid lines correspond to the full Equation 3. All distributions of dose equivalent to the revised definition of Q.

not necessitate an exclusive choice between lineal energy and LET as reference parameter. Whenever one deals with charged particles of ranges considerably in excess of 1 μm, definitions in terms of lineal energy or LET can be closely equivalent. In other cases, and this applies to photons below 200 keV and to neutrons below 0.5 MeV, the two definitions are not fully equivalent and one obtains generally larger values of the quality factor when it is referred to LET. If the definitions were to relate to restricted LET and to lineal energy in regions substantially smaller than 1 μm, the differences would largely disappear, as pointed out by Blohm and Harder[10]. Various radiobiological findings suggest that it would, indeed, be more meaningful to refer the quality factor to energy concentrations on the nanometre scale. However, at present, any such definition would be impracticable, since quality factors or dose equivalents could then not be measured. To adopt a definition in terms of lineal energy, as proposed[2], and a largely equivalent relation in terms of LET may, therefore, be the most acceptable procedure.

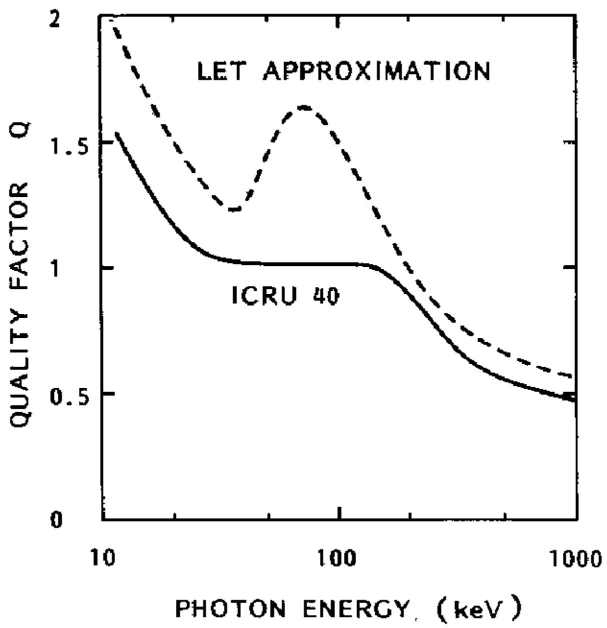

Figure 6. The solid curve gives the quality factor for monoenergetic photons according to the proposed dependence on lineal energy[2]. The broken curve results from the corresponding definition in terms of LET (see Equation 3) with cut-off 5 keV. The intermediate peak results from the low energy, short range Compton electrons.

ACKNOWLEDGEMENT

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