Rigour Within Uncertainty–An Unfinished Quest:
ICRP and High-LET Radiations

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In memory of Mavis Thomas (née Waldegrave), 1934—2005

"*The practice of radiation protection can usually be based on simplifications and approximations. . . . Conceptual clarity is . . . an essential ingredient of simplicity, and simplicity must not be confused with looseness or approximations that are admissible in 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.*"

Albrecht M. Kellerer (1990)

"*During the past two decades the concepts of radiation protection and the applicable physical quantities have drifted into what may be regarded as chaos.*"

H. H. Rossi (1995)

Abstract

The development of the current International Commission on Radiological Protection (ICRP) quantities are described and the difficulties with the application of these quantities to high-linear-energy-transfer (LET) radiations are discussed. Difficulties with the current recommendations of the commission are discussed and a critique given of the "Draft for Consultation: 2005 Recommendations of the International Commission for Radiological Protection." Suggestions for its improvement are made.

Preface

Five years ago the author wrote in a paper presented to the Ettore Majorana Centre for Scientific Culture in Erice: “At the outset of any paper on radiation protection dosimetry it is appropriate to acknowledge the crucial rôles played by both the ICRP and ICRU [International Commission on Radiation Protection Units and Measurements] in defining and establishing internationally and generally accepted quantities for use in radiological protection. The international acceptance of very similar radiation protection standards has truly been a triumph by ICRP.

“However, there are omens that all is not well with this international accord. Some countries . . . have been slow to take up the recommendations of ICRP Publication 60. . . . There are complex reasons . . . [which] might include . . . disbelief in the interpretation of the basic sciences behind the recommendations of ICRP. . . . The suggestion that there is scepticism of the ICRP recommendations is troubling because it is to some degree true. This scepticism must be dispelled if the general international agreement on radiation protection standards is to be maintained” (Thomas 2001).

On re-reading this text in 2005 the author is confirmed in these opinions and believes them to be still true today. It is therefore vital to make every effort to re-establish the international consensus on the scientific bases for the foundations for, and acceptance of, very similar radiation protection standards that had been evident prior to the publication of the commission’s recommendations in 1991 (Publication 60). An opportunity to achieve this goal is afforded by the current review by the ICRP of its fundamental recommendations.

In 2001 ICRP announced that it was to undertake a major revision of its current recommendations (ICRP 1991), including its dosimetric quantities. In April of that year, the chairman of the ICRP spoke in Bethesda to some members of the National Council on Radiation Protection and Measurements (NCRP) of the new openness in the method by which IRCP recommendations are to be reached. The commission is to be congratulated on its sentiment that it “wishes there to be an ongoing debate with an iteration of ideas . . . “ (ICRP 2001). This openness has afforded an opportunity for those individuals who make use of recommendations of the ICRP to address some of the issues already discussed in the literature, providing them an opportunity to interact effectively with the ICRP by pointing out difficulties with the *status quo* and to suggest improvement in the commission’s recommendations. The commission is to be thanked for providing the opportunity and privilege of commenting on its "Draft for Consultation: 2005 Recommendations of the International Commission for Radiological Protection" (hereinafter referred to as the 2005 draft for consultation). This act of Гласность (Glasnost) is most welcome and to be highly commended (Thomas *et al*. 2002).

Since 1991 the scientific literature has revealed concerns with some aspects of ICRP 60, particularly by dosimetrists interested in the measurement of high-energy and high-LET radiations in general, and neutrons in particular (for bibliographies see ICRP 1997; ICRU 1998; Thomas 1998-2004). Roger Clarke, chairman of ICRP, has agreed that "there have been some persistent difficulties with, and misunderstandings of, the definitions of the Commission's dosimetric quantities. The Commission will remove these by clarifying its definitions and specifying their application" (Clarke 2003).[1]

As part of the commission's review it has issued ICRP issued Publication 92 entitled *Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R)* (ICRP 2003). This is clearly an important document and might have been influential in formulating the commission's final recommendations but its advice appears only to have been partially adopted in the 2005 draft for consultation (see following paragraph).

In the autumn of 2004 the commission posted in its web site its draft for consultation and invited both institutional and individual comment (ICRP 2004).

The current status of the review may be found on the website of the ICRP and in summary is as follows: "The public consultation on the draft Recommendations of the ICRP is now completed, and ICRP is delighted to report that we have had an overwhelming response with detailed and very constructive proposals from organisations and individuals all over the world. ICRP intends to consult in the near future on the 'foundation documents' underpinning the Recommendations. Comments on the 'foundation documents' will also be taken into account in the review and revision of the draft Recommendations. Depending on the outcome of the review process, a second, shorter round of consultation on an updated draft may be necessary" (ICRP 2005).

[1] For more than 25 years (1968—1996) the author was an active participant in the work of both the ICRP and ICRU including participation in the drafting of many of the reports cited in this paper. For the past eight years he has written several papers attempting to correct inconsistencies on the part of ICRP. He therefore takes his share of blame for any confusion that may arise from the "persistent difficulties with, and misunderstandings of, the definitions of the Commission's dosimetric quantities" referred to by Chairman Clarke.

ICRP Publication 60–Some Aspects of a Controversial Document

An editorial in the journal *Radiation Protection Dosimetry* has discussed some of the dosimetric aspects of controversy generated by the publication of ICRP Publication 60. "One of the major purposes of Publication 60 issued more than a decade ago was the clarification and simplification of the Commission's recommendations on dosimetry. Two new quantities, the effective dose and the equivalent dose, were introduced and the radiation weighting factor was developed to be 'broadly compatible with the values of Q . . . [paragraph 25]. Drawing a parallel with its predecessor the dose equivalent, the equivalent dose also combined absorbed dose with a factor that is related to the biological effect of a particular type of radiation. Both the International Commission on Radiation Units and Measurements (ICRU) and the ICRP have stated that absorbed dose is the most important or fundamental physical quantity employed to specify a quantity of radiation [ICRP (2001), ICRU (1976)]. Both commissions have also recognised the need for measurements or calculations to specify a value for an amount of radiation received. The operational quantities initially developed by ICRU in 1985 and slightly modified in 1988 embraced the concept that ambient dose equivalent and personal dose equivalent (then called individual dose equivalent) were to be determined at a point [ICRU (1985, 1988)].

"The ICRP dosimetric quantity, equivalent dose, developed in 1990 represents an average over a tissue or organ that is weighted for the radiation quality. ICRP Publication 60 indicates that the radiation weighting factor, w_R, is 'independent of the tissue or organ' considered. In a symmetrical way, the tissue weighting factor, w_T, is intended to be independent of the type and energy of the radiation incident on the body. This apparently simplified construct, with its single (whole-body) value of w_R for a given radiation, would have had the advantage of permitting simple arithmetical revisions of the values of equivalent doses should changes in the recommended values of w_R be necessary in the future. It is worth noting that, in view of the ease by which simple arithmetical operations may now be made, it is no longer necessary to sacrifice rigour for ease of computation when a radiation protection quantity is defined. As Albrecht Kellerer pointed out in 1990 this apparent simplicity offered by an assumed tissue-independent w_R is not appropriate for an actual radiation field such as that produced by low energy neutrons where values of $\overline{Q}$ may differ considerably between, for example, the tissue of the breast, for which a large value of $\overline{Q}$ would be obtained, and the bone marrow where secondary gamma-rays from the neutrons would predominate, yielding a lower value for $\overline{Q}$. In retrospect the Commission may have fallen victim to the law of unintended consequences (see for example references ICRP [1997], Dietze and Siebert [1994], and Yoshizawa et al. [1998])" (Thomas *et al.* 2002).

If judged by the subsequent controversy generated in the scientific literature the attempt at "simplification" in ICRP 60 was a signal failure.

The Necessity for Rigour in the Definition of Radiological Protection Standards

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science."

William Thomson, Lord Kelvin 1824—1907

At the present time radiation protection standards inevitably depend upon judgements based on an immature knowledge of the fundamental sciences. Nevertheless, it will be suggested that within this rather wide envelope of basic uncertainty there seem to be no reason why protection quantities cannot be defined with sufficient rigour to facilitate their use in dosimetry but with sufficient flexibility to suit more academic needs (Lindell and Thomas 2001).

An analogy may be helpful. When Cristoforo Colombo sailed west out of Saltés on 3 August 1492, in command of three ships all determined to reach India, he clearly understood the vast difference between accuracy and precision. Maps were indifferent, drawn by the unsophisticated and embellished with warnings such as "Here be serpents". There was no global positioning system in place. There was no hope of accurate predictions of the fleet's landfalls. On the other hand it was vital to ensure precision in understanding the three ships' relative positions at all times so that the fleet remain intact to ensure an eventual safe landfall. As Kellerer teaches us, in radiation protection rigour is the necessary skeleton that supports the system of measurement and computation.

Very few would mount an argument against the application of rigour to radiation protection practice. Indeed the benefits of a rigorous approach to fundamental concepts seem almost axiomatic and include

- The necessary compliance with scientific (mainly physical) laws and mathematical logic.
- The establishment of a sound basis for legitimate approximations.
- Consistent dosimetry which, in turn, leads to
  - Demonstration of compliance with limits imposed for legal and administrative reasons.
  - The development of reliable data for future epidemiological studies.
  - Avoidance of confusion.
  - Public confidence and education.

Duality, Ambiguity, and Rigour. Rigour and ambiguity are antithetical. Fortunately in all of science ambiguity may be avoided by following the "Golden Rule," which is to define its necessary quantities and models rigorously and <u>in only one way</u>. Ambiguity is often the mother of dilemma and history has proved it to be so for radiation protection because this golden rule has often been violated: "Almost without realising the fact we have slowly slipped into a dichotomy in which protection standards are expressed in ICRP quantities that (ICRP says) are not measurable (but may be calculated) and the operational quantities, by which compliance with dose limits may be demonstrated, defined by the ICRU" (Thomas 1997).

The history of the evolution of the current dual system of quantities is long and complex and the interested reader is referred to ICRP Publication 74/ICRU Report 57 and to Thomas (2001) where more detail is given. In brief, the origins of this dichotomy began in the early seventies with the discussions on the interpretation of the definition of quality factor, was extended by the introduction of the dose equivalent indexes by the ICRU (1976, 1980), and was subsequently modified to the ambient dose equivalent in 1985 (ICRU 1985, 1988). With time the two systems have diverged to the point where they now seem to drive a wedge between those radiation protection personnel who are studying the physical effects of radiation and those who are studying the biological effects of radiation. (Thomas *at al*. 2001). Indeed, by 1995 this divergence was extreme enough to elicit the protest from Rossi quoted at the heading of this paper. There is some irony in the fact that it was "the late Harald Rossi [who] used to stress the distinction between a limitation system and an assessment system (ICRU 1986)" (Lindell 2001).

Lindell defends the dual system of limiting quantities and protection quantities and suggests that the fact that the protection (assessment) quantities are, in his terms, "not measurable" is inconsequential and even advantageous because it emphasises the purpose of the protection quantities, which is "for calculation and prospective use." On the other hand, he suggests, the operational quantities that are measurable are retrospective in their application. He concludes: "ICRP, for good reasons, has been rather relaxed with its definition so that the calculated magnitude of Effective Dose is somewhat ambiguous. However, this is in line with the Commission's generous, and appropriate, recommendations on the needed accuracy" (Lindell 2001). Similar views have been expressed earlier by Sinclair (1996). This author believes that this logic is based on a distinction without a difference and the resultant harm done by this relaxed approach far outweighs any perceived benefits.

Measurability, Accuracy, and Precision–Certainty in an Uncertain World. The subtle distinction between "not measurable" and "determinable" invoked by Lindell and others is one of the major causes of the evolution of a dual system of radiation protection quantities (limiting [or protection] quantities and operational quantities). Kellerer (2004) correctly draws a distinction between the adjectives "determinable" and "measurable."

The term "measurable" is generally used in the sense defined in the physical sciences. The value of a physical quantity may sometimes be directly measured. More frequently, and particularly with derived quantities, the value of a physical quantity may be "determined" by <u>measuring</u> the values of some of its constituent physical quantities to which it is related in a known way, that is expressed by an equation compliant with the laws of physics and mathematical logic. Thus the definition of "measurable" may also include "calculable" provided the method of calculation is constrained by the same principles. However, the converse is not true and it does not follow that because the value of a quantity may be calculated (determined) that it might be considered measurable in the sense meant by physicists. If a quantity is constructed of one or more components that intrinsically do not obey the laws of physics its value can be calculated (or determined) but it is nevertheless unphysical.

Thomas *et al.* (2002) have commented that in many cases (in ICRP and NCRP recommendations) " . . . the terms accuracy and uncertainty are used interchangeably. In future recommendations (of ICRP), some definitions of the terms used would be helpful. The uncertainty cannot be considered to be identical to the absolute accuracy of the prediction of 'the probability and severity of the consequent health effects' (ICRP 2001) that must inevitably be very much larger than a factor of 1.5 (typical upper limit to the required precision for dosimetry) in either direction, and some would argue might be more than an order of magnitude greater" (NCRP 1997).

Consequences and a Solution. The current existence of a dual system of radiation protection quantities does not inspire public understanding or confidence in our system of radiation protection standards. It does not seem wise to give the impression that we are keeping two sets of books.

ICRP's 2005 draft for consultation reinforces this flaw in two ways. Firstly, in paragraph 55, it states that "effective dose is . . . in principle as well as in practice a non-measurable quantity." Nevertheless, E is determinable by current techniques of measurement combined with calculation. Furthermore, only minor modifications in the definition of effective dose would make the quantity measurable in the strictest sense of the term. Secondly, in paragraph 83 of the 2005 draft for consultation the commission continues to recommend the use of ambient dose equivalent for area monitoring despite the reported flaws of this quantity for neutrons (see Ferrari and Pelliccioni 1998). Further controversy over the dual system of radiation protection quantities might be avoided by softening this apparent *imprimatur* of the ambient dose equivalent to the exclusion of better alternatives now in general use.

It is suggested that the commission review its use of language to determine whether its benefits outweigh the concomitant misunderstanding introduced. A single system of quantities would bring radiological protection (radiotoxicology) back into line with the normal practice of the mother discipline of toxicology. The distinction between the protection and the operational quantities would be eliminated with great benefits and yet carry no corresponding detriment.

External Exposure and High-LET Radiations

The Importance of High-LET Radiations. High-LET radiations are of increasing interest in radiological protection for the reasons given below. It is important that the radiation protection community address the issues of high-LET radiation dosimetry before the application of these radiations becomes widespread because

- High-LET exposures make up 10—20% of work force exposures (comparable with internal exposures).
- Air- and cabin-crew exposures to a mixed radiation field, including neutrons, are among the highest quasi-occupational exposures.
- The number of people exposed to high-LET radiations will almost certainly increase in the future.
- The probability that exposure to high-LET radiations presents some risk at low doses is almost certainly greater than that for low-LET exposures.

The Impact of High Energies. Increasing energy leads to more complex radiation fields and the approximations made for the simple radiation fields generated by low-energy photons cannot apply. One must first understand the complicated case before attempting to make valid simplifying assumptions. The recent history of the dosimetric concepts for radiological protection has been an attempt to maintain the approximations that are satisfactory for low energies and apply these concepts to higher energies where they are unsatisfactory.

- Low-energy photons: Because only low-LET charged particles (electrons) are generated in tissue the ICRP paradigm (for both internal and external exposure) is to constrain the value of the important radiation-weighting factors (RBE, $\overline{Q}$, H*(10), and w_R) to the value 1.
- For neutrons, high-energy photons, and high-LET particles both the absorbed dose and LET (dE/dX) distributions may vary greatly with location in the body. The values of average organ quality factors, $\overline{Q}_T$, may show a correspondingly wide variation between tissues. Figure 1 (Figure 49 of ICRP Publication 74) shows this well where calculated values of the relative contributions of specific organs to effective dose equivalent and equivalent dose are compared. The calculations are made for the adult human computational models (phantoms) ADAM and EVA. In the figure below the case for incident neutrons of energy 100 keV is shown and the values of the average organ dose quality factors $\overline{Q}_T$ are given. Values of $\overline{Q}_T$

are seen to range between 1.2 and 8.8 with a tissue-weighted average quality factor for the whole body of 7.1. The value of the radiation-weighting factor, w_R, recommended in ICRP Publication 60 was 16.

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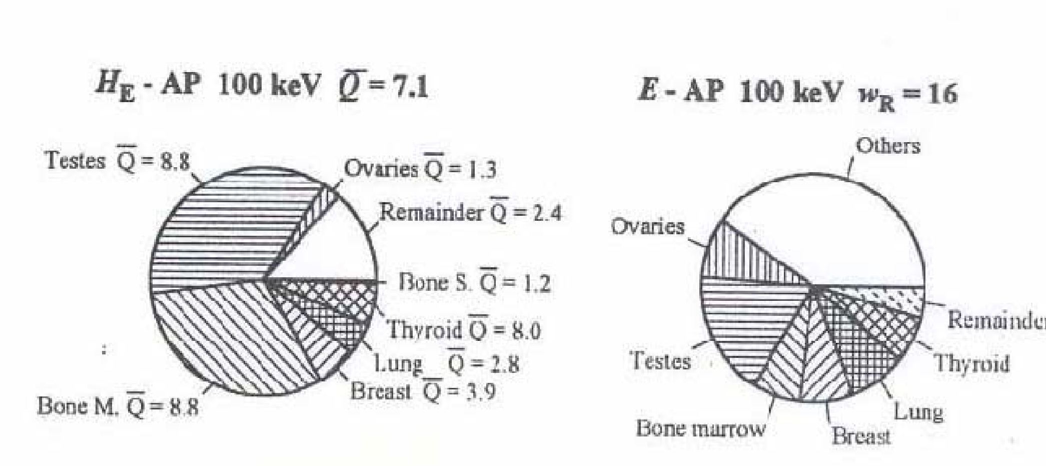

Figure 1. Relative contributions of specific organs to effective dose equivalent, H_E, and to effective dose, E, for 100-keV incident neutrons in AP irradiation geometry on an adult human computational model (mean of values calculated in ADAM and EVA) (ICRP Publication 74, fig.49)

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Historically High-LET Radiations Have Been a "Cinderella" and Urgently Need ICRP's Immediate and Focussed Attention

- **Before 1985–**"external" and "internal" modes of exposure were treated, almost distinctly and separately, by two committees of ICRP:

  Committee 2: Protection against radiation from internal radioactive substances

  Committee 3: Protection in medicine

- **After 1985–**Committee 2, Radiation Protection Standards, was charged with applying a unified approach to both exposure modes. However, external pressures directed the early effort of the new committee largely towards internal exposure modes (*e.g.*, Chernobyl [1986], radon inhalation, standard man, etc.).

However, since 1985 two important reports on external radiations have been published: ICRP Publication 74/ICRU Report 57, *Conversion Coefficients for Use in Radiological Protection against External Radiation* (1997/8) and ICRP Publication 92, *Relative Biological Effectiveness (RBE), Quality Factor (Q), and Radiation Weighting Factor (w_R)* (2003). The latter is a recent serious attempt to address the issues raised by dosimetry for external exposure to high-LET radiations.

Absorbed Dose and Modified Absorbed Doses

"Absorbed dose is the physical quantity underlying the whole of operational protection and the recommendations of ICRP. It has to be supplemented by the dose equivalent and the effective dose equivalent to take account of the differing biological properties of some radiations and the different sensitivities of body tissues but both these are nothing more than weighted absorbed doses" (Dunster 1988).

The traditional policy that the physical quantity absorbed dose is the basic physical quantity for radiological protection dosimetry is reaffirmed in the 2005 draft for consultation. Curiously, in its endorsement, the ICRP seems to be at great pains to stress that "Absorbed dose is defined in terms that allow it to be specified at a point, but it is used in this report . . . to mean the average dose over a tissue or organ." The point is obscure and might be attributed to manifestation of mathematikophobia. Point functions may readily generate average values for any desired volume of tissue by the process of integration.

Some clarification of this issue is provided in the 2005 draft for consultation, which pronounces, unconvincingly to this writer, that "the averaging of absorbed dose and the summing of mean doses in different organs and tissues of the human body, as given in the definition of all the protection quantities, is only possible under the assumption of a linear dose-response relationship with no threshold (LNT)" (ICRP 2005). Yet another manifestation of mathematikophobia*?*

In view of the complex interactions that are induced by ionising radiation at the molecular, atomic, and nuclear levels in biological systems it would be naive to believe that a crude macroscopic quantity such as absorbed dose would correlate well with biological outcomes. More than thirty years ago Rindi and Thomas (1972) suggested that such a view might be a "red herring" for high-LET radiations when ionisation density becomes an important additional physical correlate. Dietze and Menzel (2004) have recently written an excellent and contemporary critique of the limitations of absorbed dose.

The adoption of the concept of absorbed dose in the fifties was quickly followed by a succession of the modified absorbed doses referred to by Dunster. To abuse a well-known aphorism: "The Devil is in the modifications"[2] and there have been many such details. To list but a few "details":

- Absorbed dose (*circa* 1940)
- RBE dose (1948)
- Dose equivalent, H (ICRP Publication 4, 1965)
- MADE (ICRP Publication 21, 1973)
- Effective dose equivalent, H_E (ICRP Publication 26, 1977; first applied only to internal exposure but extended to include external exposure in 1980)
- Dose equivalent indexes (ICRU Report 33, 1980)
- Ambient dose equivalent, H*(d) (ICRU Reports 39 and 42, 1985)
- Effective dose, E (ICRP Publication 60, 1991)

Indeed the many such changes in radiation protection terminology over the past fifty years, often for insubstantial reasons, led to the wry comment: "It seems that to every problem in health physics there is a solution that requires the invention of a new 'quantity'" (Anonymous 2003).

The Evolution of Quality Factors–Alias Radiation-Weighting Factors

With the invention of particle accelerators and the copious production of neutrons it soon became clear that ionisation density was an extremely important additional physical parameter to be taken into account in radiological protection. Thus as early as 1935 experiments at the Crocker Laboratory on the Berkeley campus gave an early indication that not all roentgens were created equal and it was reported that

"Lawrence . . . exposed $120 worth of rats near the beryllium target of the 27-inch (Crocker Laboratory) cyclotron and at the Sloan machine in San Francisco. The neutrons appeared to be

[2] Said to be a corruption (perversion) of the French aphorism "*Le bon dieu et dans le detail*" attributed to Gustave Flaubert.

about ten times as effective as X-rays per roentgen in altering the makeup of the rodent blood, or five times as effective per unit of ionization since (they estimated) a roentgen of neutrons made twice the ionization in rat tissue that a roentgen of x-rays did. Since the standard tolerable limit of X-rays was 0.1 r/day, they recommended prudently that the maximum for n-rays be 0.01 r/day" (Heilbron and Seidel 1989).

These differences in biological response per unit "dose" were accommodated by the application of a radiation-weighting factor first named the relative biological effectiveness (RBE). Subsequently recommended values of RBE for radiological protection of humans were, of necessity, extrapolated from animal experiments in a manner judged to be prudently conservative (ICRP 1955). In order to avoid the possibility of confusion between experimental values of RBE and the administrative nature of the "RBEs for radiation protection" the latter were renamed "quality factors, Q" by the ICRP (1964). The earliest recommended values of quality factor were specified spanning ranges of a factor of about 2 both in Q and LET. This was deliberately done to emphasise the uncertainty in the values of quality factor.

To meet this need for greater precision of measurement, while still emphasising the quite large uncertainty in the absolute values, ICRP Publication 15 specified values of Q in more detail. About twenty years after the Berkeley experiments it was possible to provide a model for a Q(L)-L relationship based on radiobiological data derived from mostly cellular radiobiology (see for example Bond 1967).

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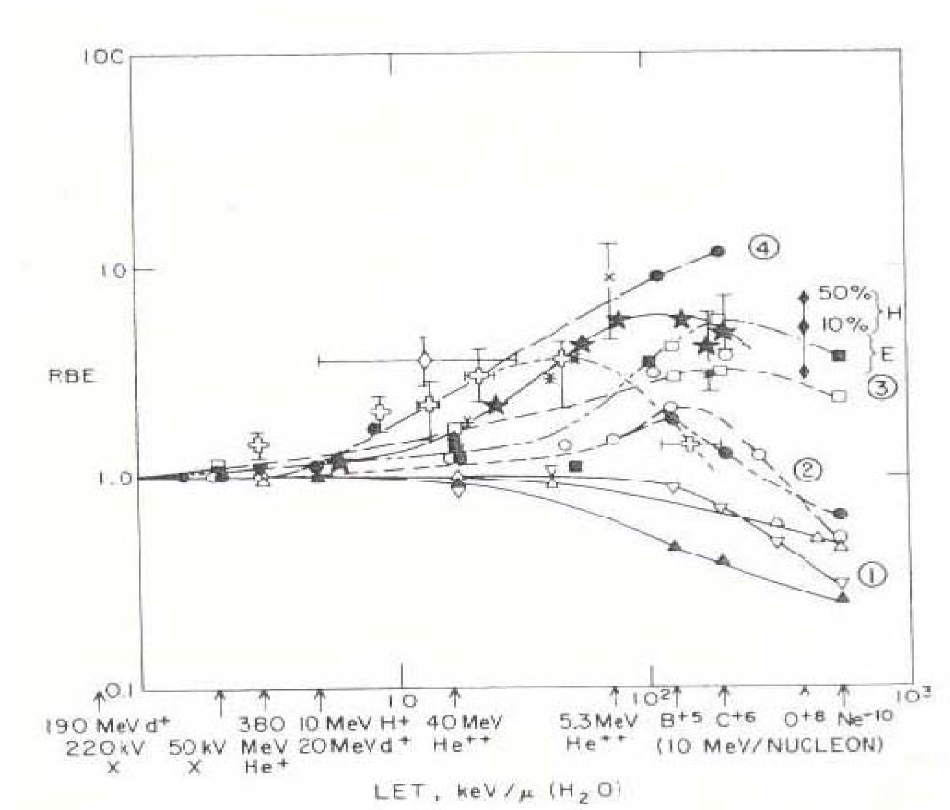

Figure 2. Experimental curves of RBE versus LET; mammalian cells are indicated by the symbols * and ¤ (BNL 50073, 1967)

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Figure 2 shows a composite array of RBE data versus LET for a variety of specimens. An NCRP committee evaluating the data suggested that mammalian cells showed similar trends, with a maximum value of RBE at an LET of about 100 keV/micron. On the basis of such analyses the ICRP recommended that a smooth Q(L)-L model be established (ICRP 1973) rather than the discontinuous histogram previously recommended (ICRP 1970). The smooth function is shown in Figure 3.

ICRP Publication 21 provided a graphical means of interpolating between these values and these recommendations for the Q-L relationship were retained in the recommendations of ICRP published in 1977 and used in calculations of the conversion coefficient data issued in ICRP Publication 51 (1987).

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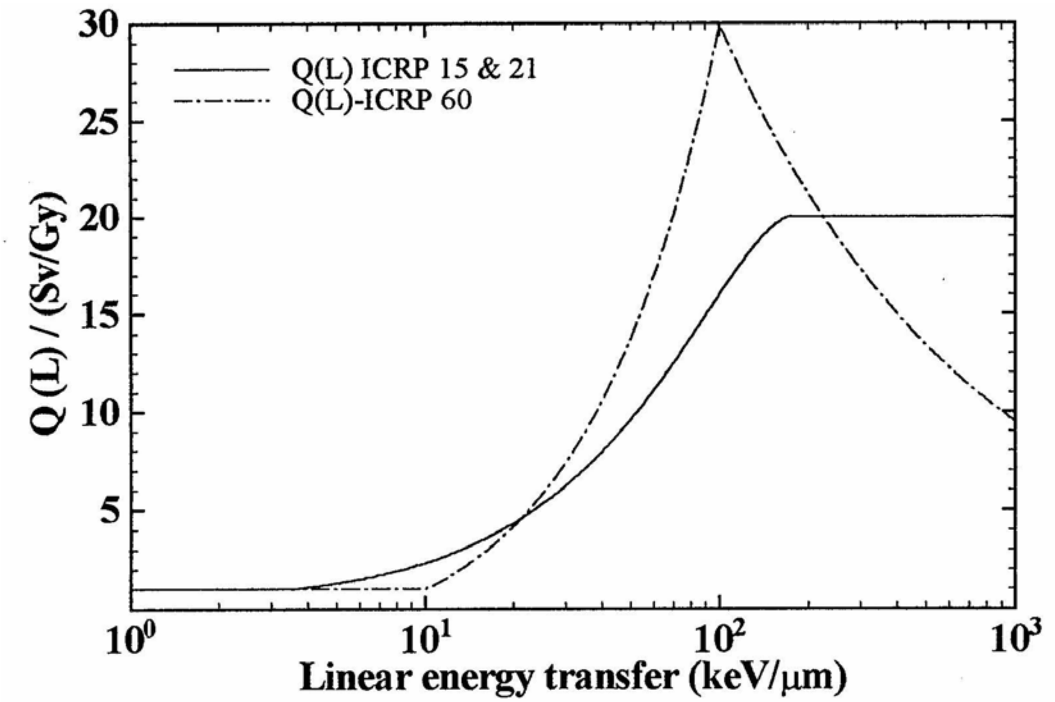

Figure 3. The two Q(L)-L relationships recommended by ICRP: the lower curve in 1971 (Publication 21) and the upper curve in 1991 (Publication 60)

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By the early 1980s the Main Commission of ICRP was increasingly persuaded that the values for the quality factors of neutrons had been underestimated. After its 1985 meeting in Paris the ICRP recommended a partial policy change of "an increase in Q by a factor of 2. The permitted approximation for neutrons thus changes from 10 to 20. These changes relate only to neutrons and no other changes in Q are recommended at this time" (1CRP 1985). Eventually, in 1991, ICRP endorsed a revised Q(L)-L relationship, also shown in Figure 3 (upper curve), that could be used for all charged particles. Visual inspection shows that this curve has an unfortunate cusp at an LET of about 100 keV/micron.

The assessment of an appropriate radiation-weighting factor for neutron exposure is fraught with difficulty. A fundamental problem for neutron exposures lies in the lack of any adequate human epidemiological data. Recent studies show that neutrons contributed only 1—2% of the total absorbed dose to the survivors of the Hiroshima A-bomb survivors–too small to give any clue as to the risks associated with neutron exposure and of the neutron RBE. The conclusion appears to be that no useful information on neutron risks may be obtained from the Hiroshima study (Hunter and Charles 2002; Little 2003; Straume *et. al*. 2003).

As already discussed "RBEs for radiological protection" (variously referred to in the literature by the symbols Q, $\overline{Q}$, and w_R) have been assessed by extrapolation from data measured in small biological systems (*e.g*., cells, small mammals) to man. Such a step is difficult for many reasons, including the physics of nuclear interactions and neutron scattering. The LET distribution of the radiation field in the tissue of animals exposed to neutrons is greatly influenced by the amount of neutron moderator (largely water) and thus by the size of the animal. RBEs measured in small biological systems irradiated in a neutron beam may not therefore be directly applicable to organs deep within the human body. For example, a large proportion of the absorbed dose deposited in the human body irradiated by intermediate energy neutrons is deposited *via* photon interactions (electrons) but this proportion is much lower in smaller mammals such as rats or mice (Dietze and Siebert 1994; see Figure 4). One might therefore expect that, within some limits, "RBEs for radiological protection" might decrease as the proportion of the dose contributed by photons increases or, alternatively, as animal size increases.

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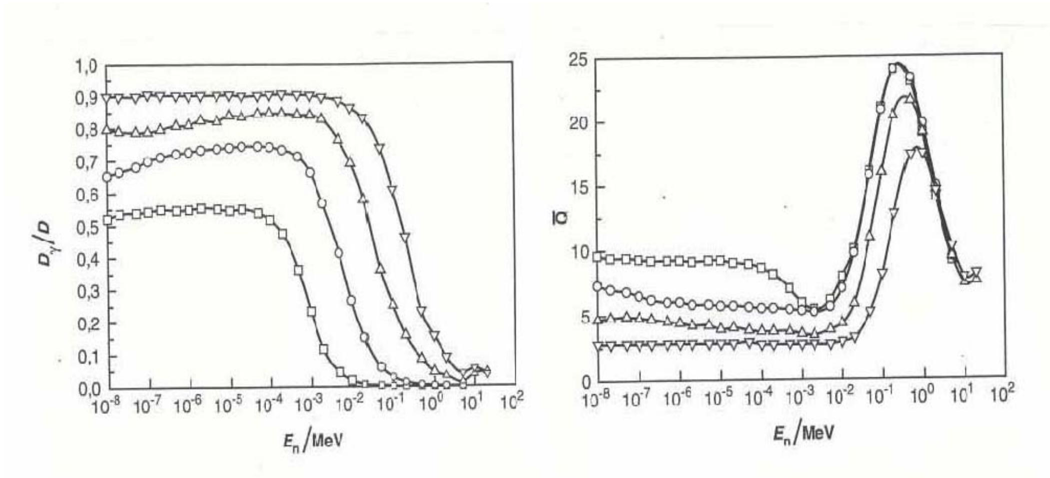

Figure 4(a). The ratio (Dγ/D) of absorbed dose contributed by photons Dγ to the total, D, versus neutron energy for neutrons incident on phantoms of different size. Key: □-Mouse; O-rat; Δ-H*(10) [value at 10mm in the ICRU sphere]; ∇-weighted mean value in the ADAM phantom

Figure 4(b). $\overline{Q}$ versus neutron energy for the conditions described for Fig. 4a (Dietze and Siebert 1994)

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ICRU Report 40, a joint ICRP/ICRU document discusses the relationship between quality factor and RBE as well as its relationship to the measures of energy deposition by charged particles in tissue, LET and lineal energy (ICRU 1986). An increase in the recommended values of $\overline{Q}$ for intermediate- and high-LET was recommended and a graphical relationship between "Q" and particle energy provided for photons, neutrons, and alpha particles. In its summary the report says that the results of the joint ICRP/ICRU review broadly provide for maximum values of RBE for fission neutrons versus fractionated gamma rays of from greater than 100 to perhaps as low as 10 or less at low doses, with many of the values in the range 15—70. ICRU Report 40 was considered but its recommendations were not adopted by the ICRP. Rather, in its recommendations in Publication 60 the ICRP made fundamental changes to its view of radiation weighting. "The Commission now believes that the detail inherent in using a formal Q-L relationship to modify absorbed dose to reflect the higher probability of detriment from exposure to radiation components with high LET is not justified because of the uncertainties in the biological information. In place of Q, or more precisely $\bar{Q}$, the Commission now selects radiation-weighting factors, w_R, based on a review of biological information, a variety of exposure circumstances, and inspection of the traditional calculations of the ambient dose equivalent" (Paragraph A9, ICRP Publication 60).

However ICRP could not abandon the Q(L)-L relationship entirely because of the commission's view that effective dose "is not measurable." It was necessary to provide an alternative quantity that was measurable and so ICRP Publication 60 provided an amended Q-L relationship with tables of recommended value of the new radiation-weighting factor, w_R (formerly $\bar{Q}$), for radiations by type and energy and, in addition, a graph of recommended values of w_R for neutrons as a function of energy, with an equation for interpolation. The commission recommended the determination of ambient dose equivalent for radiation monitoring external exposures to ionising radiation but muddied the water by adding to its advice by stating, "For radiation types and energy which are not included . . . an approximation of w_R can be obtained by calculation of $\bar{Q}$ at a 10 mm depth in the ICRU sphere . . ." (Paragraph A14, Publication 60). Although not explicit, one possible interpretation of this statement is that such calculations of $\bar{Q}$ will yield results congruent with values of w_R. In practice this is not the case (Yoshizawa *et al*. 1998).

ICRP 60 left a legacy of incongruity. For example,

- The value of $w_R = 5$ recommended for neutrons of energy less than 10 keV (intermediate-energy neutrons) is thought to be too large (Dietze and Siebert 1994). At these energies neutrons interact with human tissue to produce photons, and the dominant mechanism by which energy is deposited for deep organs is by photon interactions (electrons). This leads to the *reductio ad absurdum* that an absorbed dose deposited by photons is weighted differently, by a factor 5, if the radiation outside the body were neutrons but by a factor 1 if the radiation outside the body were photons. Proper consideration of the methods of energy deposition in tissue would more reasonably assign a value of about 2—3 for w_R in this energy region. This problem has been corrected in the 2005 draft for consultation (ICRP 2004).
- At higher energies Yoshizawa *et al*. (1998) have shown that the ratio of effective dose calculated using the recommended values of w_R to that calculated using the Q(L)-L

relationship recommended in ICRP 60 is close to unity at 20 MeV but increases steadily with energy to a value of 1.8 at 10 GeV. Such administrative differences of a factor of 2 are unacceptable and unnecessary if recommendations are written in an unambiguous manner. A change in either the Q(L)-L relationship or the values of w_R that are specified in ICRP Publication 60 (or both) is indicated. This problem has not been satisfactorily addressed in the 2005 draft for consultation (ICRP 2004).

- The specification of $w_R = 5$ for high-energy protons needs review. As a practical example, high-energy protons are present in the radiation field inside aircraft cabins flying at altitude. The use of $w_R = 5$ leads to the conclusion that protons contribute about one third of the effective dose to the exposure of passengers and crew–a value considerably higher than their relative contribution to the effective dose equivalent. This problem has been corrected in the 2005 draft for consultation (ICRP 2004) but unfortunately the ICRP does not carry over its correction to high-energy neutrons, where it equally applies .

The important influence of neutron interactions and phantom size on the radiation-weighting factor may be seen in Figure 5, taken from ICRP 92. The figure shows that the ambient dose equivalent, q*, was used to evaluate the values of w_R for neutrons recommended in ICRP Publication 60. Values of quality factor calculated using the quantity effective dose equivalent and the Q(L)-L relationship recommended in ICRP Publication 60, designated q_E, are seen to be smaller than the values of q* for neutron energies below10 MeV.

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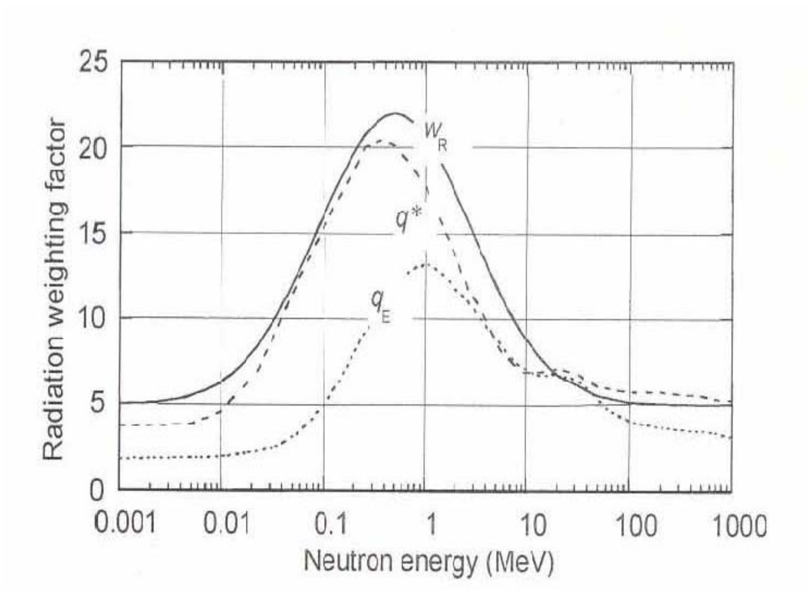

Figure 5. Radiation-weighting factor, w_R (solid curve), and the ambient quality, q* (broken curve). The dotted curve gives the effective quality factor, q_E; *i.e.*, the external weighting factor that would have made, for isotropic exposure, and with the current w_T and Q(L) values, the effective dose E equal to the effective dose equivalent, H_E (data for q* from Leuthold *et al*. [1992]; for q_E from Mares *et al*. [1997] and for an anthropomorphic phantom for energies beyond 20 MeV interpolated to the values derived by Pelliccioni [1998]) (ICRP Publication 92)

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Are Whole-Body Radiation-Weighting Factors Still Relevant?

Both ICRP publication 92 and the 2005 draft for consultation (draft Section 3.4, paragraphs 59—61) place major emphasis on the development of an average radiation-weighting factor, w_R, applicable to the whole body. This emphasis necessarily raises the fundamental question of the relevance of radiation-weighting factors to a system of radiological protection for the twenty-first century. It is to be hoped that the revised ICRP recommendations for 2005 would incorporate modern developments in dosimetry.

While some twenty-five years ago average radiation-weighting factors (then called average quality factors) were of value to the application of the "critical organ-MADE" system to radiological protection against external irradiation by neutrons. Indeed dosimetrists in general and the commission in particular were presented with “Hobson’s choice” in the matter. In that era the weighting factors provided a necessary simplification, imposed by the limitations of radiobiological information, techniques of measurement, radiation transport codes, and mathematical models of the human body, in dealing with the complexity of the radiation fields generated within the human body. This necessity was compounded by the evident mathematikophobia exhibited by the commission in its earlier recommendations and that has lingered to the present day.

However, with the great improvements, in fairly recent times, of metrological techniques, radiation transport codes, and mathematical models of the human body, the arithmetical constraints of earlier times no longer exist. Complex calculations may now be made with great facility and speed. There is much less necessity, therefore, for the “simplification” afforded in earlier times by the average radiation-weighting factors. For neutron measurements and at high energies, and particularly at accelerator laboratories, there is more interest in using conversion coefficients that relate field quantities (*e.g*., fluence) to determine the radiological protection quantities (ICRP1996, ICRU 1997, McDonald *et al*. 1998, Thomas 2003).

An average radiation-weighting factor may still be of utility for internal and external exposure by low-energy photons (where the important parameters RBE, $\overline{Q}$, H*(10), and w_R are constrained to take the value 1, thus making the any necessary calculations trivial). However, in the cases of external exposure by high-energy particles (*nota bene*: <u>including photons</u>) and for neutrons of all energies, physical considerations make the practical utility of an average radiation-weighting factor uncertain.

An important question is “what quantity does w_R modify”? The answer may be deduced from the relationship

$$E = w_R \sum_T w_T \overline{D_T} \ . \qquad (1)$$

where the symbols are well understood. Evidently, from equation (1), the answer is that it is the tissue-weighted average absorbed dose, $\sum_T w_T \overline{D_T}$, that is modified by w_R.

As we have seen both the absorbed dose and (dE/dX) distributions may vary greatly with location in the body, when it is externally irradiated by high-energy particles. In such cases values of average organ quality factors, $\overline{Q}_T$, may show a correspondingly wide variation between tissues (for example see ICRP Publication 74 for 14-MeV neutrons). Under such conditions the tissue-weighted average absorbed dose, $\sum_T w_T \overline{D_T}$, is a complicated quantity, not readily accessible to simple measurement. Thus the physical nature of high-energy radiation fields denies us the apparent simplicity suggested by equation (1).

It is suggested here that the 2005 draft for consultation needs to place greater emphasis on defining an acceptable model, or convention for the Q(L)-L relationship, from which values of $\overline{Q}$, q_E, w_R, etc., but also, and perhaps more importantly, other parameters, such as fluence-to-dose conversion coefficients, that facilitate the determination of effective dose may be derived. It seems unlikely that the commission will accept this advice because in Paragraph 59 of the 2005 draft for consultation the ICRP attempts to side-step the issue by defining it away: "The same value of radiation weighting factor . . . is applicable to all tissues and organs of the body independent of the fact that the actual radiation field may vary between different tissues and organs due to . . . the production of secondary radiations of different radiation quality in the body" (ICRP 2004). This statement in the 2005 draft for consultation seems to be at odds with the recommendations of the guest editorial of ICRP Publication 92*:* "We believe that ICRP should continue the use of w_R values that relate, for external radiation, to the incident field. For radionuclide intakes, w_R values should relate to the internal fields that cause the absorbed dose to organs and tissues" (ICRP 2003).

Here is yet again a serious source of ambiguity and indeed suggests confusion on the part of ICRP. The commission seems to have fallen victim of the danger pointed out by Kellerer a decade and half ago: "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." (Kellerer 1960).

The 2005 Draft for Consultation Recommendations are a Great Disappointment

Figure 6 shows the draft recommendations for w_R for neutrons and several problems are evident.

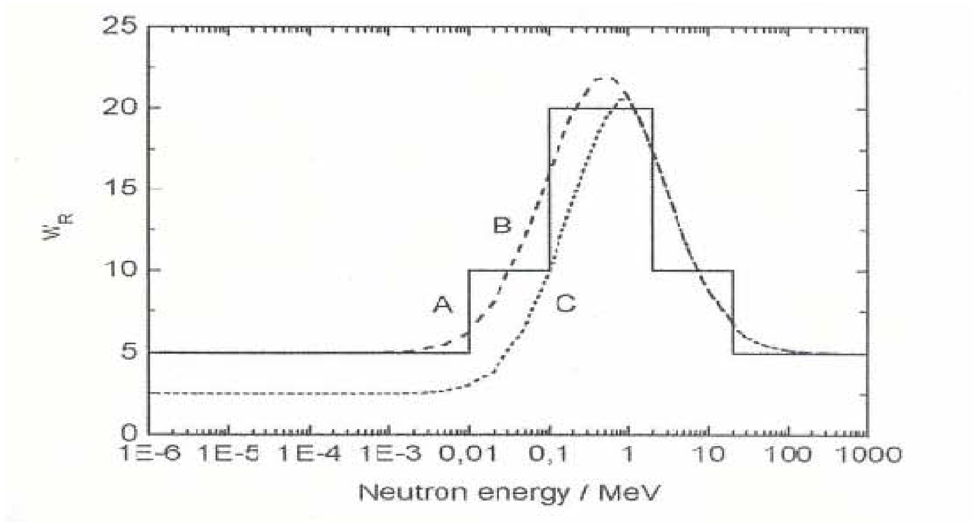

Figure 6. Radiation-weighting factor, w_R, for incident neutrons versus neutron energy; (A) and (B) are the step function and continuous function given in ICRP 60 while (C) is the curve recommended in the 2005 draft for consultation

- The Q(L)-L relationship recommended in ICRP Publication 60, now used to calculate some values of w_R, was "discredited" by ICRP Paragraph A9, ICRP Publication 60.
- Values of $q_E = 2$ were accepted for neutron energies below 1 keV and *de facto* q_E was defined to be equal to q_E in this energy region ($q_E = w_R$).
- The calculated value of $q_E \cong 13$ for neutron energies in the 1 MeV range were not accepted and w_R was set at ~ 21 (based on RBE values for <u>small</u> animals $q_E \neq w_R$).
- A fudge-equation is invoked to forge a link between values of q_E at low energies and the imposed value of w_R at 1 MeV: $w_R = 1.6q_E - 1$.
- If, after radiobiological review, the values w_R below 1 keV are acceptable but at 1 MeV unacceptable then it must be concluded that the recommended Q(L)-L relationship and the value of w_R at 1 MeV are inconsistent.

- The value of w_R of 5 recommended for high-energy neutrons is incompatible with the value of 2 recommended for high-energy protons

Goals for an "Ideal" System of Dosimetry for Radiological Protection

An ideal framework upon which to base a system of dosimetry for radiological protection would be

- Universal: applies to all radiations, whatever their energy.
- Integrated: independent of the origin of the radiation (either outside or inside the human body).
- Unambiguous: standards are set in determinable quantities (no distinction between "protection" and "operational quantities."
- Rigorous: logically and mathematically coherent and consistent with mathematical logic and physical laws.
- Stable: avoiding frequent changes in names and symbols of dosimetric concepts.

Suggestions for a Remedy to the 2005 Draft for Consultation Proposals

- Define only protection quantities and leave it to the ingenuity of dosimetrists to deduce the means of their measurement (or determination). (This step effectively abandons the dual concept of protection (limiting) and operational quantities.)
- Review the experimental and theoretical basis for the recommendations of RBE for humans, paying particular attention to the experimental irradiation conditions for small samples (animals).
- Redefine the function Q(L)-L on the basis of such a review. It would be most helpful if a figure showing the current best estimate, and therefore recommended, function Q(L) and its band of uncertainty were prepared. The form of the new function should be mathematically tractable and avoid breaks or cusps (such as are evident in the current recommendation).

It is the writer's opinion that the uncertainty in the radiobiology would permit some flexibility in the choice of Q(L) and that it is possible to recommend changes in the function from the current ICRP 60 form that would be acceptable to both the radiobiologists and the physicists and also would satisfy particular criteria that are important to ICRP and others.

- Revert to the quantity effective dose equivalent.
- The new Q(L)-L must generate values of tissue-weighted average quality factors for a selected anthropoid phantom(s) (radiation-weighting factor) consistent with the laws of physics and with radiological review suggested above. At the present time the 2005 draft for consultation suggests the following constraints (which may change with the review of the radiobiology):
  - q_E = 2 for low-energy neutrons (seems correct to the physicists and satisfies the radiobiologists and ICRP).
  - q_E = 20 for 1-MeV neutrons (satisfies ICRP) but perhaps the choice needs a better explanation than given hitherto by ICRP.
  - At high energies (hundred-MeV region) the value of w_R (q_E) for high-energy protons and neutrons should approach the same value. This is a matter of energy deposition, *i.e.*, physics and should therefore be acceptable to the radiobiologists. A value of $q_E \approx 2$ would be about right in the mid-100-MeV region

Conclusion and Personal Comment

A major problem with both ICRP 92 and ICRP 2005 draft for consultation proposals is that they appear to fix the values of w_R for neutrons to conform to a preconceived notion that w_R for "fission neutrons" must take a value of about 20. The arguments for this assertion dwell heavily on administrative and legal concerns. The radiobiological arguments are not well explained by ICRP. Indeed, there seems to be no discussion that the measured values of RBE values for cellular samples might be influenced by neutron scattering within the human body. Had measurements been made with cellular samples irradiated deep within the body (phantoms), it is likely that smaller values of RBE would have been observed than for cells exposed to unmoderated neutron fields.

Consequently there is a danger that science might be relegated to political disputes. ICRP would be better served by focussing on the relevant science that can be brought to bear and ensuring that it is the best that possibly it can be so that, in Kellerer's happy phrase, "rigour within uncertainty" may be achieved.

An important cosmetic aspect must be addressed. Some have suggested that "it doesn't seem wise to give the impression that we are keeping two sets of books." Frankly, the approach of the 2005 draft for consultation has the appearance of "cooking the books" and my guess is that ICRP will draw immediate adverse criticism if it moves in this direction. With hindsight it now seems evident that had the ICRP/ICRU Joint Task Group been convened before, rather than after, ICRP Publication 60 was issued that many of the flaws in that document could have been avoided.

This paper has drawn attention to several causes for concern in the 2005 draft for consultation. If the ICRP is not about to repeat the mistake it made with ICRP Publication 60 it would do well to carry out the necessary preparatory literature search and possibly necessary calculations before the publication of its revised recommendations, rather than afterwards only then to discover surprises followed by another decade of discontent.

The good news is that happily there is a rather simple remedy to these concerns if only ICRP can be persuaded to take it.

Acknowledgements

It is appropriate that this paper be dedicated to the memory of my wife Mavis who died recently. During the preparation of this paper Mavis shared my care with this work and it is hers as much as it is mine.

I am most grateful to the Sierra Nevada and Northern California Chapters of the Health Physics Society for the opportunity to speak at the Thirteenth Annual J. Newell Stannard Lecture Series in honour of that great scientist and human being.

This paper is not original but combines ideas from several previous papers discussing the general subject of this paper. This may explain the apparent narcissism of the many self-references. I have tried to identify wherever text has been plagiarised and to give credit to those cited. Please forgive me for my failures in this respect.

I should also like to thank Linnea Wahl (LBNL) for her advice and important help in getting the paper ready on time.

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