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THE ICRU PROPOSAL FOR NEW OPERATIONAL QUANTITIES FOR EXTERNAL RADIATION

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Report Committee 26 of the ICRU proposes a set of operational quantities for radiation protection for external radiation, directly based on effective dose and for an extended range of particles and energies. It is accompanied by quantities for estimating deterministic effects to the eye lens and the local skin. The operational quantities are designed to overcome the conceptual and technical shortcomings of those presently in use. This paper describes the proposed operational quantities, and highlights the improvements with respect to the present, legal monitoring quantities.

INTRODUCTION

The control of radiation risk by limitation and optimisation of exposure is based on the quantity effective dose for the whole body, and equivalent dose, for single organs, summing the effects from external and internal exposure⁽¹⁾. To complement these protection quantities defined by the ICRP, the ICRU defines operational quantities for external radiation in which radiation area monitoring instruments and personal dosimeters can be calibrated^(2, 3). These quantities give reasonable estimates of the protection quantities in broad energy spectra of photons or neutrons, but they are not well-suited to high-energy radiation fields in excess of a few MeV. Furthermore, their relation to the protection quantities is complex, and conversion coefficients for dosimeter calibration are published only for photons, neutrons and electrons.

Report Committee (RC) 26 of the ICRU proposes a set of operational quantities, directly related to effective dose and absorbed dose, for an extended range of particles and to a range of energies for different particles and operational quantities from 1 keV to 200 GeV.

After recalling the definition and evaluation of the protection quantities, this paper details the present operational quantities and their technical and conceptual shortcomings. The next Section introduces the proposed operational quantities, shows the conceptual simplification and metrological improvements they afford with

respect to the present quantities. The last Section highlights necessary changes to dosimeter design and calibration, in particular for neutron dosimetry.

PROTECTION QUANTITIES

The quantification of exposure to ionising radiation and the resulting radiation detriment requires a quantity which can be used indiscriminately for external and internal radiation exposure. The International Commission on Radiological Protection (ICRP) developed the protection quantities, equivalent dose in an organ or tissue and effective dose⁽¹⁾. ICRP plans to discontinue the use of equivalent dose as separate protection quantity, because it is only used to quantify deterministic effects to the extremities, the lens of the eye and the local skin, for which absorbed dose is a better estimator⁽⁴⁾. The protection quantities are used for the implementation of dose limits and for guiding quantitatively the optimisation principle.

The effective dose to the whole body is defined as

$$E = \sum_{T,R} w_T w_R D_{T,R}. \quad (1)$$

The summation extends over the incident radiation types R and the tissues or organs T with absorbed dose $D_{T,R}$ averaged over the volume of the tissue. w_R

[†]Deceased

is the radiation weighting coefficient, taking into account the effectiveness of each radiation type to create radiation damage and w_T is the tissue-weighting coefficient, accounting for the different radiation sensitivities of tissues (with $\sum w_T = 1$).

The weighting factors w_T and w_R are evaluated from clinical and epidemiological surveys and effective dose E cannot be used for individual estimates of radiation risk.

For evaluating the radiation risk in measured or calculated external fields, one relates effective dose to a quantity characterising the radiation field, for example particle fluence or, for photons, Kerma in air. Conversion coefficients h_E between the field quantity and effective dose are calculated by numerically evaluating equation (1) in a mathematical phantom⁽⁵⁾ for eight standard orientations of the radiation field (Figure 1).

With help of the energy-dependent conversion coefficients, effective dose from one type of radiation can be expressed as

$$E = \int dE_p \Phi_{E_p} h_E(E_p, \text{inc}). \quad (2)$$

In this equation, E_p stands for the kinetic energy of the particle, Φ is the fluence and h_E the fluence-to-dose conversion coefficient. ‘inc’ stands for one of the eight incident directions of the external field. The integral extends over all particle energies present in the radiation field. The absorbed dose to two critical organs, the lens of the eye and local skin, is evaluated with specific phantoms⁽⁶⁾.

The presently adopted set of conversion coefficients h_E has been published by the ICRP⁽⁶⁾.

PRESENT SYSTEM OF OPERATIONAL QUANTITIES

Protection quantities are not defined at a single point but as averages over organs or over the whole body.

Therefore, they are not accessible to direct measurement. The International Commission on Radiation Units and Measurements (ICRU) has defined a set of operational quantities, complementing the protection quantities in different measurement situations.

Definition of Present Operational Quantities

The system of operational quantities distinguishes between quantities for monitoring of individuals (personal dose equivalent) and of areas (directional and ambient dose equivalent). Presently, dose equivalent is defined as the product of an absorbed dose and a quality factor. The ICRP defines dose equivalent as⁽¹⁾

$$H = \int_{-\infty}^{\infty} Q(L) D_L(d) dL. \quad (3)$$

The absorbed dose D is evaluated at a specified depth d in the body or in a phantom, 10 mm for whole-body monitoring, 3 mm for the lens of the eye and 0.07 mm for local skin. The quality factor Q is a function of the linear energy transfer (LET or L_∞) of the particles at the interaction point⁽³⁾.

While personal dose equivalent $H_p(d)$ is defined at d mm under the ‘representative location on the body’, directional and ambient dose equivalent are defined at the specified depth in a simple geometrical phantom: the ICRU sphere with 30 cm diameter made from ICRU 4-component tissue⁽⁷⁾. Ambient dose equivalent is made independent from the direction of incident radiation by expanding and aligning all field vectors and thus giving an overestimation of the actual dose.

Table 1 gives an overview of the operational quantities thus defined and their relationship with the protection quantities^(3, 4).

For practical applications, conversion coefficients from a field quantity (fluence or air Kerma) to the operational quantity are calculated numerically in phantoms (Table 2)^(8, 9). For ambient and directional dose equivalent, the calculation is performed in the

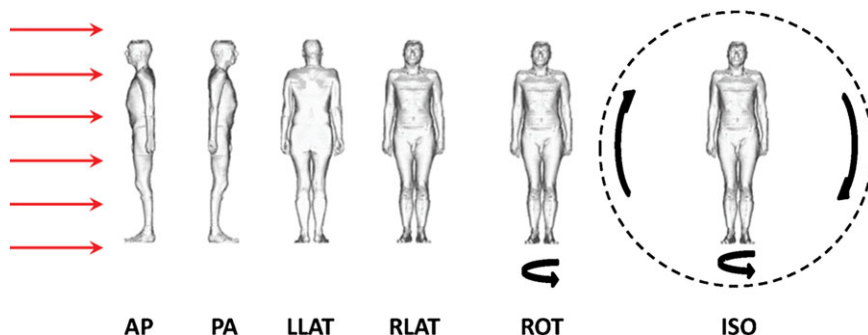


Figure 1. Six of the eight standard orientations of a numerical phantom with respect to the direction of the broad, parallel radiation field. The missing orientations are radiation emerging from a hemisphere above, or below the phantom.

ICRU sphere, whereas conversion coefficients to personal dose equivalent are calculated in a slab phantom of 30·30·15 cm³ for the whole body, in a cylindrical phantom of Ø20·20 cm³ for the lens of the eye and in cylindrical phantoms of diameters 7.3 cm and 1.9 cm and length 30 cm for local skin. The phantoms are made from 4-component ICRU tissue.

Conceptual and Technical Shortcomings

Operational quantities rely on phantoms for their definition and for the calculation of conversion coefficients from field quantities to ambient or personal dose equivalent. These phantoms introduce inconsistencies to the system of dosimetric quantities for radiation protection:

- (1) The ICRU sphere bears no resemblance to the human body used to define the protection quantity effective dose.
- (2) The evaluation of personal and ambient dose equivalent at a single, defined depth d does not reflect the geometrical complexity of the human body with numerous organs implicitly present in the definition of E .
- (3) Both the quality factor $Q(L)$ and the radiation weighting factor w_R express the effectiveness of different radiation types, but they are based on different models and are not directly comparable.

- (4) Personal dose equivalent is defined in depth d in the body, but for the calculation of conversion coefficients simple geometrical bodies like slabs, cylinders and rods are used.
- (5) The lens of the eye and the local skin are monitored with a dose equivalent quantity for deterministic effects, which depend, to our best knowledge, on absorbed dose.

The consequence of the inconsistencies (1) and (2) result in an inadequate estimate of the operational quantities for certain particles and energies, and generally differences between the conversion coefficients between field quantities and protection or operational quantities. Figure 2 illustrates this situation for photons.

Observation (3) can also be made for the quantities $H'(0.07)$ for energies over 65 keV and for $H'(3)$ for energies over 740 keV, and for personal dose equivalent at the depths d .

For neutrons, similar discrepancies exist, predominantly at intermediate and high energies (Figure 3).

OPERATIONAL QUANTITIES PROPOSED BY ICRU REPORT COMMITTEE 26

To overcome the shortcomings of the operational quantities for external radiation protection, the ICRU has called upon a Report Committee (RC 26) to make proposals for a redefinition of the operational

Table 1. Relation of protection quantities with present operational quantities.

	Whole body	Lens of the eye	Local skin
Protection quantity	Effective dose E	Equivalent dose to the lens of the eye $H_{T \text{ lens}}$	Equivalent dose to local skin $H_{T \text{ local skin}}$
Area monitoring	Ambient dose equivalent $H^*(10)$	Directional dose equivalent $H'(3, \Omega)$	Directional dose equivalent $H'(0.07, \Omega)$
Individual monitoring	Personal dose equivalent $H_p(10)$	Personal dose equivalent $H_p(3)$	Personal dose equivalent $H_p(0.07)$

Table 2. Phantoms employed to calculate the conversion coefficients from field quantities (fluence, air kerma) to protection quantities and present operational quantities.

	Whole body	Lens of the eye	Local skin
Protection quantity	Whole-body ICRP/ICRU adult reference phantoms ⁽⁵⁾	Stylised eye model embedded in whole-body phantom ⁽¹⁰⁾	10·10·10 cm ³ skin tissue phantom ⁽⁶⁾
Area monitoring		ICRU Sphere, Ø30 cm	
Individual monitoring	Slab phantom 30·30·15 cm ³	Cylinder phantom Ø20·20 cm ³	Slab phantom 30·30·15 cm ³ Pillar Phantom Ø7.3·30 cm ³ Rod phantom Ø1.9·30 cm ³

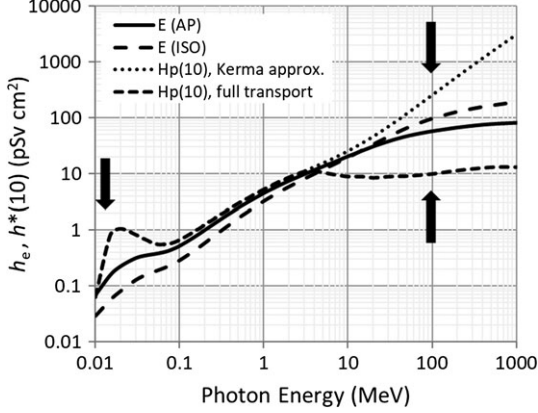


Figure 2. Conversion coefficients from photon fluence to effective dose in AP and ISO orientation E(AP), E(ISO) and to ambient dose equivalent $H^*(10)$ calculated in kerma-approximation and with full electron transport. The arrows mark energy ranges with discrepancies.

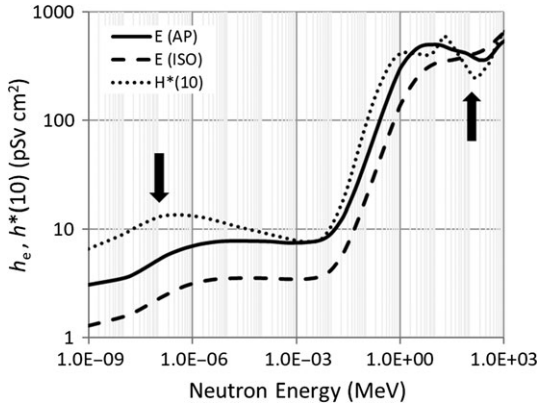


Figure 3. Conversion coefficients from neutron fluence to effective dose in AP and isotropic orientation E(AP), E(ISO) and to ambient dose equivalent $H^*(10)$. The arrows mark energy ranges with discrepancies.

quantities for external radiation. The Committee investigated the use of various depths in the specific phantoms, and combinations of depths, but also noting that several of the observed drawbacks of the operational quantities are related to the use of specific phantoms, the Report Committee decided to choose an alternative definition.

Definition of Proposed Operational Quantities

In the proposal of ICRU RC 26, operational quantities are defined as the product of particle fluence and a conversion coefficient⁽¹¹⁾. Symbolically this is written as

$$H = \Phi \cdot h_{\Phi}. \quad (4)$$

The conversion coefficients h_{Φ} are calculated as the quotient of the value of the protection quantity, evaluated in the whole-body ICRP/ICRU adult reference phantoms⁽⁵⁾ for specific directions of incidence divided by the particle fluence in absence of the phantom:

$$h_E = \frac{E}{\Phi} \text{ and } h_T = \frac{H_T}{\Phi}. \quad (5)$$

For photons, conversion coefficients can also be defined in terms of air kerma K_a . Definitions (4) and (5) ensure coherence between the values of the protection quantity for specific particle types, energy and direction of incidence and the corresponding operational quantity.

Personal dose

The quantity to monitor whole-body exposure of workers, *personal dose*, H_p , is the product of the particle fluence, Φ , and a conversion coefficient, $h_{p,i}(E_p, \Omega)$. The conversion coefficient is given by $h_{p,i}(E_p, \Omega) = E(E_p, \Omega)/\Phi(E_p, \Omega)$, where the fluence values are those for the particle type i , at each kinetic energy E_p and at each direction of incidence, Ω . For a given $|\Omega|$, the maximum value of effective dose is taken for radiation incident from left or right.

For the purpose of dosimeter type testing and calibration, conversion coefficients $h_p(E_p, \Omega)$ have been calculated between the angles 0° and 90° in steps of 15° , and for rotational and isotropic incidence. Naturally, the values of $H_p(E_p, 0^\circ)$ are numerically equal to E (AP) for the same particle energies.

The quantities *personal absorbed dose to the lens of the eye* and *personal absorbed dose in local skin* are defined in similar fashion. The conversion coefficients for these quantities are calculated as the quotients $d_{p \text{ lens}}(E_p, \Omega) = D_{p \text{ lens}}(E_p, \Omega)/\Phi(E_p, \Omega)$ and $d_{p \text{ local skin}}(E_p, \Omega) = D_{p \text{ local skin}}(E_p, \Omega)/\Phi(E_p, \Omega)$ where $D_{p \text{ lens}}$ and $D_{p \text{ local skin}}$ are evaluated in specified phantoms (Table 3).

Ambient dose

The quantity to assess areas for potential whole-body exposure, *ambient dose* H^* , is defined as the product of the particle fluence, Φ , and a conversion coefficient $h_{E_{\max}}(E_p)$. The conversion coefficients are given by $h_{E_{\max}}(E_p) = E_{\max}(E_p)/\Phi(E_p)$, where the fluence values are those for the particle type i at the point of interest, at each energy, E_p . The maximum of effective dose is taken from the values for the incident directions AP, PA, LLAT, RLAT, ROT, ISO, SS-ISO and IS-ISO (for most particle

Table 3. Phantoms employed to calculate the conversion coefficients from field quantities (fluence, air kerma) to protection quantities and proposed operational quantities.

	Whole body	Lens of the eye	Local skin
Protection quantity	Whole-body ICRP/ICRU adult reference phantoms	Stylised eye model embedded in whole-body phantom	10·10·10 cm ³ skin tissue phantom
Area monitoring	Whole-body ICRP/ICRU adult reference phantoms	Stylised eye model embedded in whole-body phantom	Slab phantom 30·30·15 cm ³ ^a
Individual monitoring	Whole-body ICRP/ICRU adult reference phantoms	Stylised eye model embedded in whole-body phantom	Slab phantom 30·30·15 cm ³ ^a Pillar Phantom Ø7.3·30 cm ³ ^a Rod phantom Ø1.9·30 cm ³ ^a

^aPhantoms have a 2 mm layer of ICRP skin. ⁽¹²⁾

types, only a subset of these directions has been considered).

The maximisation over directions of incidence assures conservativeness of the quantity with direction of radiation for area assessments, just as the expanded and aligned radiation field for the present ambient dose equivalent $H^*(10)$. Figure 4 illustrates the construction of H^* from effective dose E for different directions of incidence.

For the area monitoring of a potential dose to the lens of the eye and local skin, the quantities *directional absorbed dose to the lens of the eye* $D'_{\text{lens}}(E_p, \Omega)$ and *directional absorbed dose to local skin* $D'_{\text{local skin}}(E_p, \Omega)$ have been defined in the same way as the analogue quantities for personal monitoring. The numerical values of their conversion coefficients are identical to those for D_p lens and D_p local skin for the slab phantom.

Table 3 shows the phantoms employed for the calculation of conversion coefficients and Table 4 summarises the newly defined operational quantities.

Particle types and energy range of new operational quantities

Conversion coefficients for the new quantities for whole-body monitoring, H^* and H_p , will be made available for photons, electrons, positrons, neutrons, alpha particles, positive and negative muons and positive and negative pions, for energies up to 10 GeV, or for some particles to 100 or 200 GeV. The energy range for other quantities will be 50 MeV

CONSEQUENCES FOR RADIATION DOSIMETRY

As seen in Figure 4 on the example of photons, the proposed definition of the operational quantities entails changes of the energy dependence of the

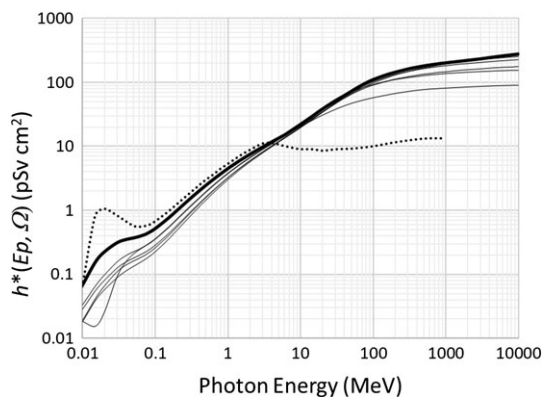


Figure 4. Construction of conversion coefficients for H^* (fat black line) for photons as the maximum, at each particle energy, of the family of effective dose conversion coefficients for different incident directions (thin black lines). Energy dependence of the present operational quantity $H^*(10)$ added for comparison (dotted line).

conversion coefficients. This change must be considered in the calibration coefficients of dosimeters. For photons, present ‘good’ dosimeters will show an overresponse below $E_p = 30$ keV. This can be corrected by a thicker attenuation layer above the detector element. Many dosimeters are based on linear combination of multiple detector elements, a re-design of the evaluation algorithm should be able to absorb the different energy dependence of the measured quantity.

The conversion coefficients for standard calibration fields ⁽¹³⁾ are subject to change, as illustrated in Table 5 and Figure 5 for neutron calibration sources.

Neutron area monitors are designed such that the energy dependence of their response follows closely

Table 4. Relation of the protection quantities with operational quantities proposed by ICRU Report Committee 26.

	Whole body	Lens of the eye	Local skin
Protection quantity	Effective dose E	Equivalent dose to the lens of eye H_T lens	Equivalent dose to local skin H_T local skin
Area monitoring	Ambient dose H^*	Directional absorbed dose to lens of the eye D'_{lens}	Directional absorbed dose to local skin $D'_{local skin}$
Individual monitoring	Personal dose H_p	Personal absorbed dose to lens of the eye D_p eye lens	Directional absorbed dose to local skin D_p local skin

Table 5. Spectrum-averaged conversion coefficients for standard neutron calibration sources.

	$h^*(10)$ (pSv cm ²)	h^* (pSv cm ²)
²⁵² Cf	385	351
²⁴¹ Am-Be	392	427

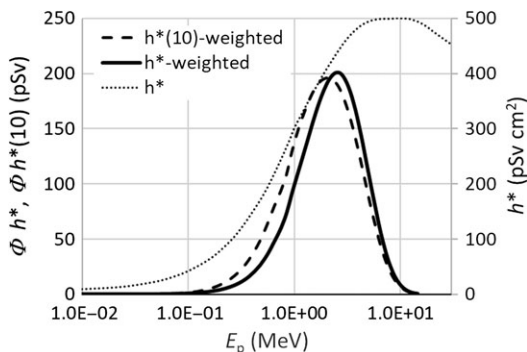


Figure 5. Ambient dose (equivalent) fluence spectrum of a ²⁵²Cf neutron source weighted with $h^*(10)$ and with h^* (left-hand scale), conversion coefficient h^* (right-hand scale).

that of the conversion coefficient to ambient dose equivalent $H^*(10)$. The influence of the new quantity H^* on the response of commercially available rem-counters is illustrated in Figure 6.

CONCLUSIONS

ICRU RC 26 proposes a set of operational quantities for protection from external radiation which is more coherent with the protection quantities effective dose E and equivalent dose to an organ H_T , or absorbed dose, D_T . The operational quantities H^* , H_p , D'_T and D_p are defined as the product of a field

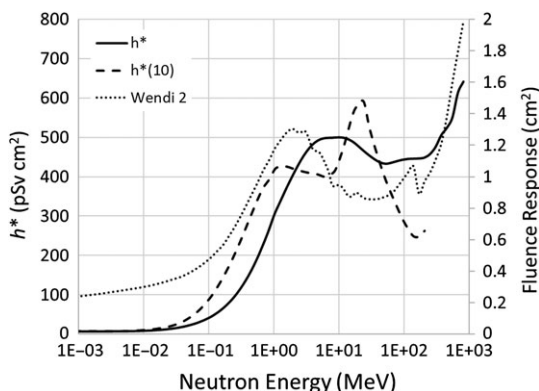


Figure 6. Fluence to ambient dose (equivalent) conversion coefficients h^* and $h^*(10)$ for neutrons above 1 keV (left-hand scale) and response functions the energy-compensated rem-counter Thermo Electron Wendi 2. As for $H^*(10)$, a radiation field specific adjustment of the calibration coefficient will remain necessary.

quantity (mostly fluence) and a conversion coefficient. Most conversion coefficients are calculated with the same phantoms as the protection quantities, those for local skin with a very similar one.

The introduction of these quantities into radiation protection practice would require a recalibration of all monitors or dosimeters, and in some cases a re-design, for example for photons at energies below 30 keV.

Presently, the proposal of ICRU RC 26 is submitted to the ICRU main commission and the ICRP main commission, which has initiated a public consultation before a common publication.

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