Journal of Amran University 05 (2025) p. 157-174

مجلة جامعة عمران

journal homepage: www.auy.edu.ye

The Operational and Protection Quantities for External Radiation Exposure: A review

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Received 8 Jan. 2025; accepted in final form 1 May 2025.

Abstract

The concepts of protection and operational quantities are fundamental in radiation protection, essential for assessing and controlling exposure to ionizing radiation. Protection quantities are designed to reflect the risk of stochastic health effects resulting from radiation exposure. However, these quantities cannot be measured directly, as they depend on knowledge of the energy deposited in organs and tissues, as well as the biological sensitivity of different tissues. To address this gap between theoretical risk assessment and practical measurement, operational quantities were introduced. These serve as practical surrogates that conservatively estimate protection quantities under specific exposure conditions. In the context of external radiation exposure, it is crucial to evaluate the effects associated with the radiation exposure processes to ensure adequate protection for workers, members of the public and healthy parts of patients. For this purpose, the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP) have provided definitions and phantoms for protection and operational quantities in reports such as ICRU-57 (1998) and ICRP-74 (1997). Furthermore, the ICRU-95 (2020) report suggests a different approach to defining operational quantities, based on the same phantoms used for defining protection quantities, making them good estimators of protection quantities. This research provides a summary of the definitions and phantoms for both protection and operational quantities. Understanding the relationship between operational and protection quantities is essential for ensuring accurate monitoring and control of radiation exposure. Therefore, this study presents definitions for radiometric and dosimetric quantities, as well as their relationships. Additionally, comparisons between protection and operational quantities are discussed, drawing on all relevant ICRU and ICRP reports.

Keywords: Physical quantities, Operational quantities, Protection quantities, Radiation, Conversion coefficients.

الملخص: تُعدّ الكميات الحماية والكميات التشغيلية مفهومين أساسيين في الحماية من الإشعاع، ويُستخدمان لتقييم ومراقبة التعرض للإشعاع المؤين. صُممت كميات الحماية لتعكس خطر الآثار الصحية العشوائية الناجمة عن التعرض للإشعاع. لا يُمكن قياس كميات الحماية بشكل مباشر، إذ تتطلب معرفة الطاقة المُخزّنة في الأعضاء والأنسجة، بالإضافة إلى الحساسية البيولوجية للأنسجة المختلفة. ولسد هذه الفجوة بين تقييم المخاطر النظري والقياس العملي، تم إدخال الكميات التشغيلية. تُعدّ الكميات التشغيلية بدائل عملية تُقدّر كميات الحماية بشكل متحفظ في ظل ظروف تعرض محددة. في حالة التعرض الخارجي للإشعاع، من الضروري تقييم الآثار المرتبطة بعمليات التعرض للإشعاع لتوفير حماية كافية للعاملين وأفراد الجمهور، بالإضافة إلى الأجزاء السليمة من المريض. لهذا الغرض، قدمت اللجنة الدولية لوحدات وقياسات الإشعاع (ICRU) واللجنة الدولية للحماية من الإشعاع (ICRP) مثل تقارير ICRU-57 (1998) وICRP-74 (1997) التعريفات واشكال الفانتوم (Phantoms) لكميات الحماية والكميات التشغيلية. كما يقترح تقرير ICRU-95 (2020) نهجًا مختلفًا لتعريف الكميات التشغيلية، وهو نهج يعتمد على نفس الأشباح مثل تعريف كميات الحماية، مما يجعلها مقدرين جيدين لكميات الحماية. كما تم العرض في هذا البحث ملخصًا للتعريفات واشكال الفانتوم (Phantoms) لكميات الحماية والكميات التشغيلية. في الحماية من الإشعاع، يعد فهم العلاقة بين الكميات التشغيلية وكميات الحماية أمرًا ضروريًا لضمان المراقبة والتحكم الدقيق في التعرض للإشعاع. لذلك، تقدم هذه الدراسة تعريفات الكميات الإشعاعية والقياسية للجرعات وعلاقاتها بينهما. كما قدم هذا البحث مقارنات بين كميات الحماية والكميات التشغيلية من خلال جميع تقارير ICRU وICRP.

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1. Introduction

All human beings are exposed to ionizing radiation from natural and artificial sources. Exposure to natural radiation arises from both cosmic and terrestrial sources, as well as from natural radioactivity in our food and drink. Throughout history, man has been exposed to natural radiation, and it is impossible to decide whether this radiation has been harmful or beneficial to the human species [1]. Therefore, radiation protection aims to safeguard human health from the harmful effects of ionizing radiation while allowing its beneficial use in medicine, industry, and research [2], [3].

The International Commission on Radiological Protection (ICRP) and International Commission on Radiation Units and Measurements (ICRU) defined two types of quantities for use in Radiological protection. The ICRP and ICRU developed protection quantities and operational quantities, respectively [2], [3]. Furthermore, the International Commission on Radiological Protection (ICRP) established a system of radiation protection for workers exposed occupationally to ionizing radiation, which was extended to all members of the public.

The fundamental characteristic of the protection quantities is that they are only calculable [4] [5]–[8]. For this purpose, the ICRU developed operational quantities to provide a reasonable estimate of the value of protection quantities associated with potential exposure [10, 11, 12]. Physical quantities and operational quantities are the basis for measuring external radiation. National and international standards laboratories maintain standards and reference radiation fields that are specified and described in terms of these quantities for calibration of instruments and dosimeters. Also, the physical quantities are related to operational and protection quantities by conversion coefficients which can be calculated using radiation transport codes such as Monte Carlo, deterministic algorithms, and appropriate mathematical models [9]–[13]. [7], [14], [15].

The conversion coefficients are based on values of the protection or operational quantities to radiometric or dosimetric quantities such as absorbed dose in local skin, absorbed dose in the lens of the eye, and effective dose. The conversion coefficient assists us in determining the risk or biological nuisance that can be caused by external exposures. The conversion coefficients for monoenergetic photons, electrons, positrons, and neutrons beams, at different incidence angles have been used [5], [16]–[18].

The ICRU-95 report [19] suggests a different approach to defining operational quantities, one that is based on the same phantoms as the definition of protection quantities, making them good estimators of protection quantities by definition. ICRU-95 report introduces the new quantities and gives conversion coefficients for a wide range of particles and energies, including for the first time, particles occurring only in high-energy radiation fields.

This research presented a summary of the latest findings of studies and reports of definitions and phantoms for protection and operational quantities. This study aims to define the radiometric quantities, dosimetric quantities, protection quantities, and operational quantities and to compare them. These quantities have an important role in reducing and assessing exposures for workers medically, industrially, and in research in procedures resulting in potentially large doses. The operational quantities are considered the basis of the research in radiation protection in the Radiation and Nuclear Systems. The study of comparison between protection and operational quantities is useful to improve standards of protection for workers in procedures resulting in potentially high exposures in complex radiation fields, such as interventional radiology, nuclear medicine, and new developments in the medical, industrial, and scientific [20], [21].

2. The evolution of quantities historically

In ICRU-19 report (1971), the absorbed dose index and dose equivalent index were recommended as the operational quantities for exposure to external radiation. In ICRU-20 report (1971), there is consideration of the use of MADE (maximum dose equivalent in an irradiated body).

ICRU-39 (1985) and ICRU-43 (1988) were developed the operational quantities. These reports defined ambient dose equivalent, directional dose equivalent, and individual dose equivalent, as operational quantities [22], [23]. The quantities for individual monitoring were partly modified in ICRU-51 report (1993), with individual dose equivalent being changed to personal dose equivalent. Information on the application of these quantities was given for photons and electrons in ICRU-43 and ICRU-47 reports (1988; 1992) and for neutrons in ICRU-66 report (2001) [24], [25].

Sets of values of conversion coefficients to these quantities from radiometric and dosimetric quantities were published by ICRU in Reports43 and 47, and jointly with ICRP in ICRU report 57 (1998)and ICRP publication 74 (1996) [2], [3].

The ICRP-103 [26], reviewed the protection quantities, including effective dose, originally introduced in ICRP-60 report (1990). Conversion coefficients from physical quantities to the revised protection quantities were published in ICRP-116 report (2010) [15], [26].

The ICRU-95 report (2020) report introduces the new quantities and gives conversion coefficients for a wide range of particles and energies, including for the first time, particles occurring only in high-energy radiation fields. ICRU-95 report suggests a different approach to defining operational quantities, one that is based on the same phantoms as the definition of protection quantities, making them good estimators of protection quantities by definition [19].

3. Quantities and Fundamental Units

3.1 Radiometric quantities

These radiometric quantities are important in radiation dosimetry, which has been determined dosimetric quantities.

3.1.1 The flounce, *Φ*, is the number of particles incident *dN* to the sphere of cross-sectional area *da*, as shown in Figure.1, [27], [28], thus:

$$\Phi = \frac{dN}{da} \qquad (1)$$

The unit of flounce is cm^{-2}

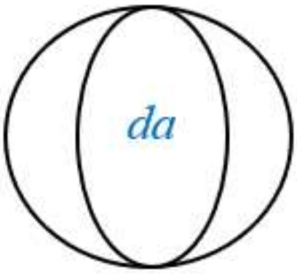

Figure (1): sphere of cross-sectional area (*da*).

3.1.2 The energy flounce (ψ) [29], [30], is the ratio between the radiant energy incidence *dR*; and the sphere of cross-sectional area *da*, the relation given by:

$$\psi = \frac{dR}{da} \qquad (2)$$

For a monoenergetic radiation beam, *R* is the product of *N* number of the particle and their energy, *E* (*dR= dN*E*)**,** the unit of energy flounce is the joule.cm^{-2}.

3.2 Dosimetric quantities

3.2.1 KERMA (Kinetic Energy Released per unit Mass)

The Kerma for ionizing uncharged particles, is the quotient of dE_{tr} by d*m*, where dE_{tr} is the mean sum of the initial kinetic energies of all the charged particles liberated in a mass d*m* of a material by the uncharged particles incidence [27], [31]–[34], thus:

$$K = \frac{dE_{tr}}{dm} \qquad (3)$$

$$dE_{tr} = (R_{in})_u - (R_{out})_u^{nonr} + \sum Q \qquad (4)$$

$(R_{in})_u$ = Radiant energy of uncharged particles entering volume *V.*

$(R_{out})_u^{nonr}$ = Radiant energy of uncharged particles leaving volume *V, except* that which originated from radioactive losses of kinetic energy by charged particles while in volume *V.*
$\sum Q$ = Net energy derived from rest mass in volume *V*.
The unit of Kerma is $J.kg^{-1}$. The special name for the unit of Kerma is gray (*Gy*).

Although Kerma is a quantity that concerns the initial transfer of energy to matter, it is sometimes used as an approximation to the absorbed dose. The total Kerma is therefore usually divided into two components:

- **The collision Kerma (*K_{col}*),** is that part of Kerma that leads to the production of electrons that dissipate their energy as ionization in or near the electron tracks in the medium and is the result of Coulomb force interactions with atomic electrons. Thus, the collision Kerma is the expected value of the net energy transferred to charged particles per unit mass at the point of interest, excluding both the radioactive energy loss and energy passed from one charged particle to another.
- **The radioactive Kerma (K_{rad})** is that part of Kerma that leads to the production of radioactive photons as the secondary charged particles slow down and interact in the medium. These interactions most prominently are bremsstrahlung as a result of Coulomb field interactions between the charged particle and the atomic nuclei, but can also result from annihilation in flight.
The total Kerma K is thus given by the following:

$$K = K_{col} + K_{rad} \qquad (5)$$

A quantity related to the Kerma, termed the collision Kerma, has long been used as an approximation to absorbed dose [27, 26, 4] when radioactive losses are not negligible
The collision Kerma *Kcol,* is given by the following:

$$K_{col} = \frac{dE_{tr}^{n}}{dm} \qquad (6)$$

$$E_{tr}^{n} = (R_{in})_u - (R_{out})_u^{nonr} + \sum Q - R_u^r = E_{tr} - R_u^r \qquad (7)$$

Where R_u^r is the radiant energy emitted as radioactive losses by the charged particles, which themselves originated in volume *V*:
Quantities related to the Kerma termed the collision Kerma, has long been used as an approximation to the absorbed dose, when radioactive losses are not negligible [35]–[38].
The collision Kerma, (K_{col}), excludes the radioactive losses by the liberated charged particles, and for a flounce, *Φ*, of uncharged particles of energy *E* in a specified material is given by.

In the ICRU-95, the collision Kerma, (*Kcol*), excludes the radioactive losses by the liberated charged particles, and for a flounce, *φ*, of uncharged particles of energy E_p in a specified material is given by [19]

$$K_{col} = \Phi E \frac{\mu_{en}}{\rho} = \Phi E \frac{\mu_{tr}}{\rho}(1-g) = K(1-g) \qquad (8)$$

where μ_{en}/ρ is the mass energy-absorption coefficient and μ_{tr}/ρ is the mass energy-transfer coefficient of the material [31], for uncharged particles of energy *E***,** and *g* is the fraction of the total kinetic energy of liberated charged particles that would be lost in radioactive processes in that material [39], [40].

In dosimetric calculations, the collision Kerma, K_{col}, can be expressed in terms of the distribution, *Φ*, of the uncharged-particle flounce with respect to energy as:

$$K_{col} = \int \Phi E \frac{\mu_{en}}{\rho} dE = \int \Phi E \frac{\mu_{tr}}{\rho}(1-g) dE = K(1-\overline{g}) \qquad (9)$$

Where $\bar{g}$ is the mean value of g averaged over the distribution of the Kerma with respect to the electron energy.

3.2.1.2 The radioactive Kerma (*K_{rad}*), is that part of Kerma that leads to the production of radioactive photons as the secondary charged particles slow down and interact in the medium. These interactions most prominently are bremsstrahlung as a result of Coulomb field interactions between the charged particle and the atomic nuclei, but can also result from annihilation in flight. The total Kerma *K*, is thus given by the following:

3.2.2 The Kerma rate

The Kerma rate, $\dot{K}$, is the quotient of d*K* by *dt*, where *dK* is the increment of Kerma in the time interval dt [37], [41], thus:

$$\dot{K} = \frac{dK}{dt} \qquad (10)$$

Unit: J kg^{-1} s^{-1}

The special name for the unit of Kerma rate is Gray per second (Gy s^{-1}).

3.2.3 Absorbed dose

The absorbed dose [42]–[44] is given by the equation

$$D = \frac{d\varepsilon}{dm} \qquad (11)$$

Where d*ε* is the mean energy imparted by ionizing radiation to matter of mass *dm*, as given by:
The unit of absorbed dose is *J kg^{-l}*. The special name for the unit of absorbed dose is gray (*Gy*).

$$d\varepsilon = (R_{in})_u - (R_{out})_u + (R_{in})_c - (R_{out})_c + \sum Q \qquad (12)$$

$(R_{in})_u$ = Radiant energy of uncharged particles entering volume *V***.**

$(R_{out})_u$ = Radiant energy of uncharged particles leaving volume *V***.**

$(R_{in})_c$ = Radiant energy of charged particles entering volume *V***.**

$(R_{out})_c$ = Radiant energy of charged particles leaving volume *V***.**

$\sum Q$ = Net energy derived from rest mass in volume *V***.**

The unit of absorbed dose is *J kg^{-l}*. The special name for the unit of absorbed dose is gray (*Gy*).

3.2.4 Absorbed dose rate

The absorbed dose rate, $\dot{D}$, is the quotient of *dD* by *dt*, where *dD* is the increment of absorbed dose in the time interval *dt*, [37][45], thus:

$$\dot{D} = \frac{dD}{dt} \qquad (13)$$

Unit: $J\ kg^{-1}\ s^{-1}$.

The special name for the unit of absorbed dose rate is Gray per second ($Gy.s^{-1}$) [46].

3.2.5 The relations between basic dosimetric quantities

***Charged particle equilibrium:**

According to ICRP-116 [19], the charged particle equilibrium (CPE) in a volume of interest means that the energies, numbers, and directions of the charged particles are constant throughout this volume. In a point of irradiated medium is a condition in which for every charged particle that leaves the point in the volume element, another charged particle with the same sort; energy, and direction enters the volume element [37, 38, 39]. This is equivalent to saying that the distribution of charged particle energy radiance does not vary within the volume. In particular, it follows that the sums of the energies (excluding rest energies) of the charged particles entering and leaving the volume are equal, [47], [48], [49].

The electrons set in motion by the Compton effect (which is the predominant effect in biological tissues) are preferentially directed forward. There are three situations:

- At the surface of the medium located at the beam penetration level, the energy transferred is greater than the energy absorbed, because most of the electrons will finish their course outside the sphere of interest cantered on each point in the middle of Figure 2a.

$$K > D$$

- In-depth, the energy transferred is equal to the energy absorbed. It is said that electronic balance is achieved: The number of electrons leaving the sphere is equal to the number of electrons ending there in Figure 2b.

$$K=D$$

- At the surface of the medium located opposite the penetration of the beam, the energy transferred is less than the energy absorbed, because more electrons come to complete their course in the sphere, having been generated upstream, there are no electrons generated in the sphere Figure.2c [15].

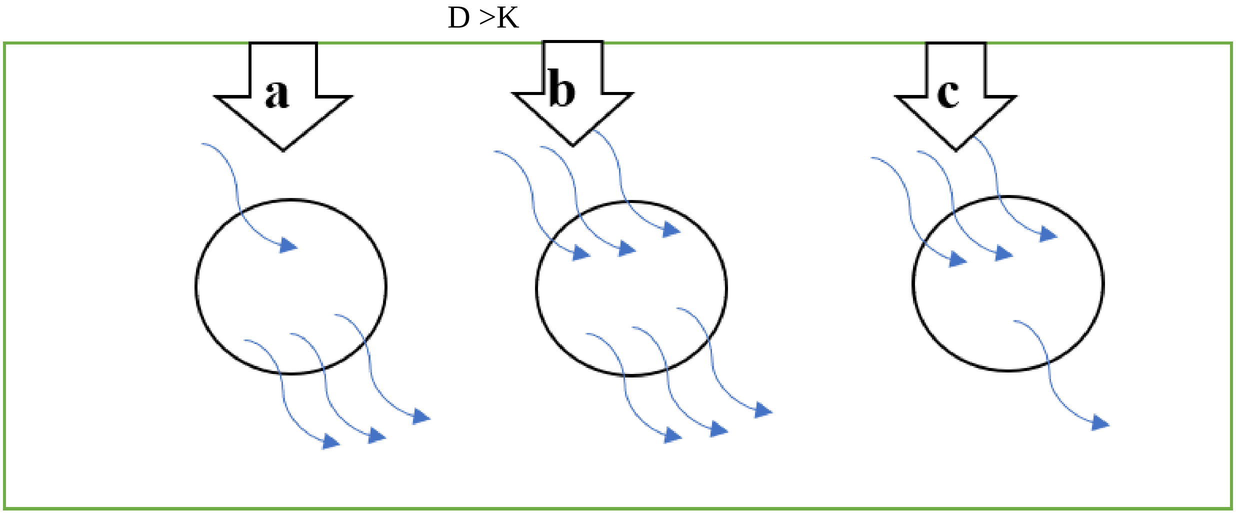

Figure (2): Relation between absorbed dose and Kerma.

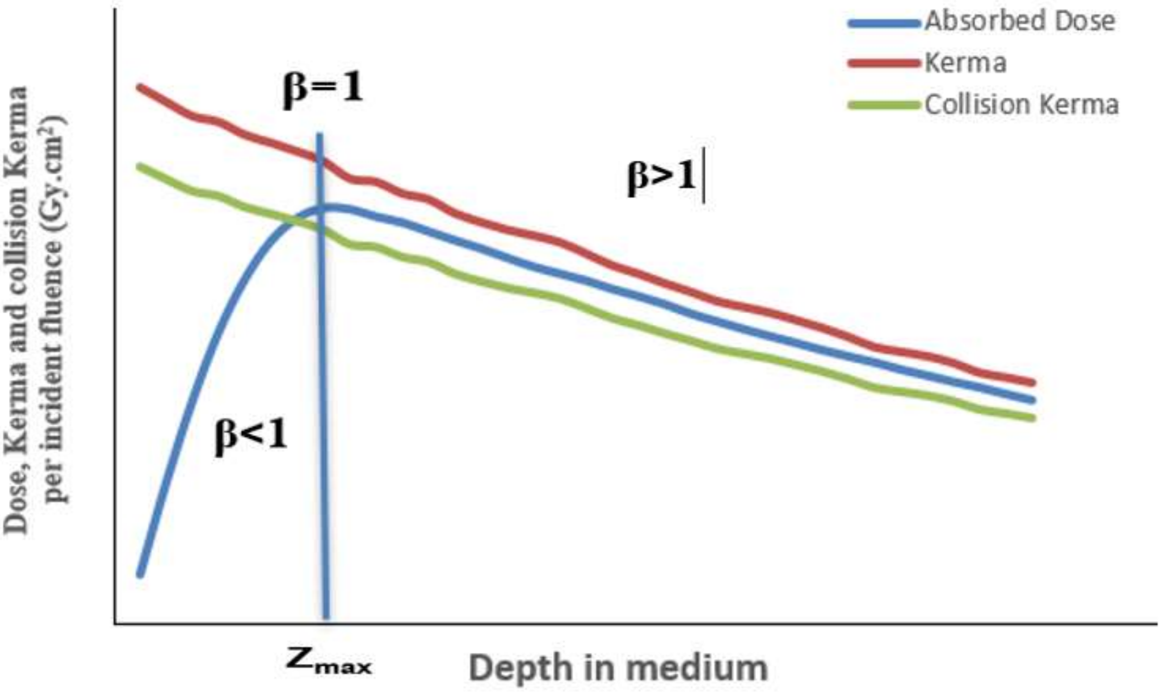

Figure (3): Relation between absorbed dose and collision Kerma.

The β equal to Kerma per Dose.

The state of constant ionization is named charged particle equilibrium (CPE), because in this situation the charged particles which are liberated in the volume d*V* and leave the volume are balanced, in number and energy, by particles which were liberated elsewhere, and that enter volume d*V*, as illustrated in Figure (3), [50]. When the number of interactions is so small that the flounce may be considered constant inside the medium, the variation of K_{col} with depth will be in accordance with Figure (4-a). The expectation value of the total ionization in volume d*V* increases initially but then decreases slowly with increasing depth in the medium, when attenuation of photon beam is considered. The state at depths beyond the maximum of ionization is called transient charged particle equilibrium (*TCPE*), as illustrated in Figure (4-b). Usually, however, it is considered that the flounce decreases exponentially with depth in the material, with similar behaviour for K_{col} as shown in Figure (3), [51]. The Kerma is maximum at the surface and decreases with depth. The absorbed dose, initially build up to a maximum value and then decrease at the same rate as Kerma.

3.2.6 Kerma Approximation

Kerma is sometimes used as an approximation to the absorbed dose. The numerical value of the Kerma approaches that of the absorbed dose to the degree that charged particle equilibrium exists, that radioactive losses are negligible, and that the kinetic energy of the uncharged particles is large, compared to the binding energy of the liberated charged particles [52], [53].

3.3 Definitions of protection quantities

For protection against exposure radiation, it important to know the distribution absorbed dose and dose equivalent in body with an accuracy that will depend on the purpose for which the information it to used [44]. The protection quantities include: effective dose, *E*; organ equivalent dose, H_T, organ absorbed dose, D_T, as shown in Figure (4).

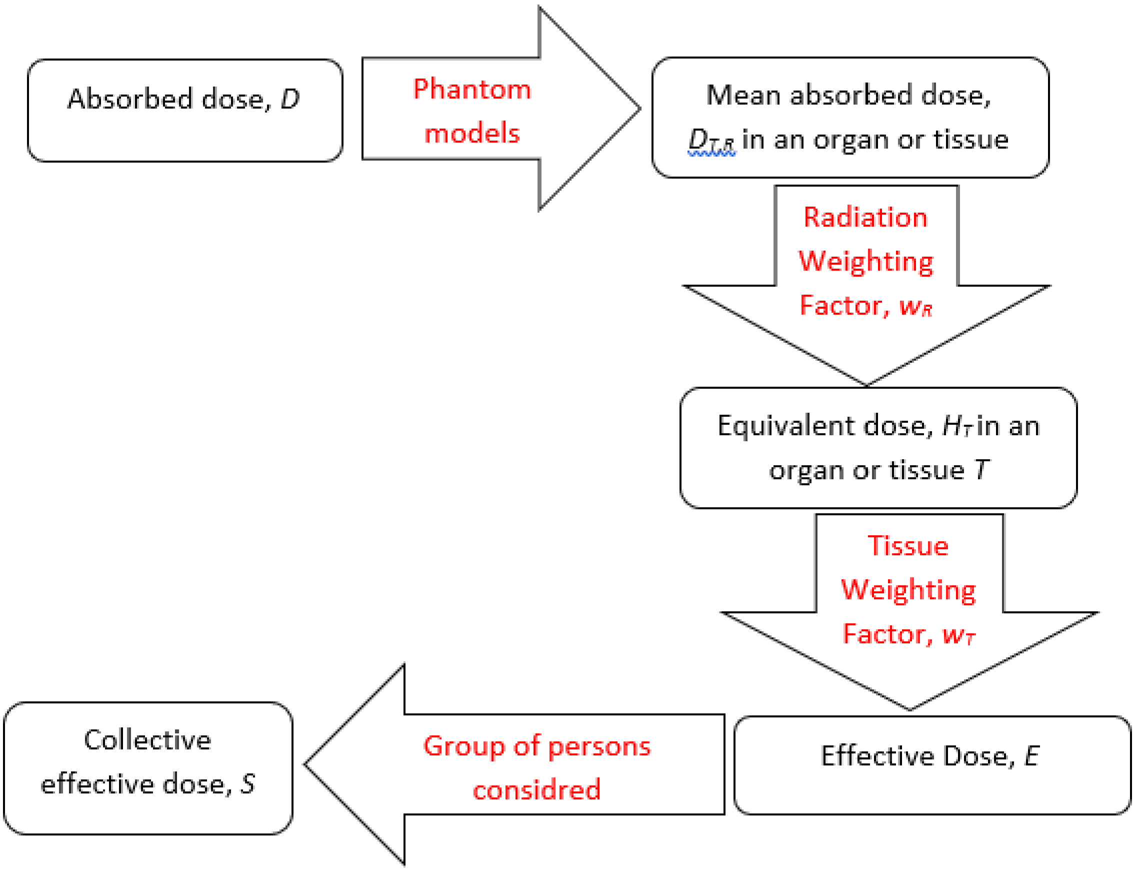

Figure (4): System of dose quantities for use in radiological protection.

3.3.1 Mean absorbed dose

The mean absorbed dose, D_T [54], [55], equals the ratio of the mean energy imparted to the organ or tissue, ε_T, and m_T, the mass of the organ or tissue, thus:

$$D_T = \frac{\bar{\varepsilon}}{m_T} \qquad (14)$$

The unit of mean absorbed dose is $J.kg^{-1}$, and its special name is Gray (Gy). The mean absorbed dose in an organ is sometimes termed organ dose.

3.3.2 Equivalent dose, $H_{T,R}$

The equivalent dose in an organ or tissue *T* is given by:

$$H_{T,R} = D_{T,R} w_R \qquad (15)$$

Where, $D_{T,R}$ is the mean absorbed dose from radiation *R* in an organ or tissue *T*, and w_R is the radiation weighting factor as summarized in Table (1) . The unit for equivalent dose is joule per kilogram ($J.kg^{-1}$) and its special name is sievert (*Sv*) [15].

$$H_{T,R} = \sum_R D_{T,R} w_R \qquad (16)$$

Table (1): Radiation Weighting Factor, w_R.

Radiation types	Radiation Weighting Factor, w_R
Photon	1
Electron and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	Continuous function of neutron energy, *Eq.* (17)

To calculate the radiation weighting factor for neutron using the following Equation:

$$w_R = \begin{pmatrix} 2.5+18.2e^{-(\ln(E_n))^2/6} & E_n < 1\,MeV \\ 5.0+17.0e^{-(\ln(2E_n))^2/6} & 1\,MeV \le E_n \le 50\,MeV \\ 2.5+3.25e^{-(\ln(0.04E_n))^2/6} & E_n > 50\,MeV \end{pmatrix} \qquad (17)$$

3.3.3 Effective dose, H_E

The tissue-weighted sum of equivalent doses in all specified organs and tissues of the body, given by the expression.

$$H_E = \sum_T H_{T,R} w_T = \sum_T w_T (\sum_R D_{T,R} w_R) \qquad (18)$$

Where H_T is the equivalent dose in an organ or tissue T. $D_{T,R}$ the mean absorbed dose in an organ or tissue T from radiation of type R, and w_T is the tissue weighting factor, as summarized in Table (2), [15], [56].

The sum is performed over all organs and tissues of the human body considered to be sensitive to the induction of stochastic effects. The unit for effective dose is joule per kilogram (J kg^{-1}), and its special name is sievert (Sv).

Table (2): Tissue Weighting Factor, w_T, ICRP

Tissue	w_T	$\sum w_T$
Red bone-marrow, Colon, Lung, Stomach, Breast, Remaining Tissue[1]	0.12	0.72
Gonads	0.08	0.08
Bladder, Esophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04
Total		1.00

3.3.4 Collective effective dose, *S*

The collective effective dose is defined as the sum of all individual effective doses in a group of people over the time period or during the operation being considered due to ionizing radiation. The collective dose is given by [26].

$$S = \sum_i E_{i,} N_i \qquad (19)$$

Where:

E_i is the average effective dose for a subgroup i.

N_i is the number of individuals in this subgroup i.

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[1] Remainder tissues: adrenals, extra thoracic region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (male), small intestine, spleen, thymus, and uterus/cervix (female).

The unit of the collective effective dose is joule per kilogram ($J.kg^{-1}$) and its special name is man sievert (*man-Sv*) [57].

3.4 Definitions of operational quantities

Operational quantities aim to provide a reasonable estimate, generally conservative, for the value of the protection quantities related to an exposure or potential exposure of persons under most irradiation conditions. The operational quantities include the fowling [15].

3.4.1 Dose equivalent

The dose equivalent, *H,* is defined as a product of *Q* and *D* at a point in tissue [15], [58]–[62], by thus:

$$H = Q.D \qquad (20)$$

Where *D* is the absorbed dose and Q is the quality factor at that point, The unit of dose equivalent is joule per kilogram ($J.kg^{-1}$), and its special name is sievert (Sv) [15], [63], [64]. The quality factor equals to 1 for photons and electrons.

Quality factor dependence of *Q* on (LET) (*L*) was given by ICRP [45]. The quality factor *Q* at a point in tissue is given by:

$$Q = \frac{1}{D}\int_{L=0}^{\infty} Q(L)\,D_L\,dL \qquad (21)$$

Where *D* is the absorbed dose at that point, D_L is the distribution of *D* in unrestricted linear energy transfer L at the point of interest, and *Q(L)* is the quality factor as a function of *L*. The integration is to be performed over D_L, due to all charged particles, excluding their secondary electrons [15].

3.4.2 Operational quantities for area monitoring

Two operational quantities are defined for dose assessment of whole-body exposures: ambient dose equivalent $H^*(10)$ for prospective assessments of radiation exposure at workplaces and in the environment with survey instruments and personal dose equivalent $H_p(10, \alpha)$ for retrospective assessment of dose received by a person with personal dosimeters [65]. Both quantities have in common that they are evaluated in 10 mm depth within a reference phantom. The operational quantities are evaluated by radiation transport calculation in the ICRU sphere, slab and cylinder phantoms. The numerical values of conversion coefficients to the operational quantities have been published jointly in ICRP-74 and ICRU-57 reports.

3.4.2.1 Ambient dose equivalent, *H**(10):

For area monitoring, the operational quantities for assessing effective dose are the ambient dose equivalent denoted $H^*(10)$. The ambient dose equivalent is the dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at depth of 10 mm on the radius opposing the direction of the aligned field. The unit of ambient dose equivalent is the joule per kilogram ($J.kg^{-1}$) and its special name is sievert (*Sv*) [66]. Ambient dose equivalent for strongly penetrating radiation, d =10 mm).

3.4.2.2 Directional dose equivalent:

For area monitoring, the quantities for assessing the dose to the skin and the extremities (hands, wrists, and feet), as well as the dose to the lens of the eye, is the directional dose equivalent, denoted as $H'(d, \Omega)$.

The directional dose equivalent, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at *d,* on a radius in a specified direction, Ω. The unit of directional dose equivalent is joule per kilogram ($J.kg^{-1}$) and its special name is sievert (Sv). Directional dose equivalent (for weakly penetrating radiation, d= 0.07 and 3 mm).

3.4.3 Operational quantities for individual monitoring

3.4.3.1 Personal dose equivalent:

Individual monitoring of external exposure is usually performed with personal dosemeter worn on the body, and the operational quantities defined for this application takes this situation into account. For individual monitoring, the operational quantities are the personal dose equivalent, denoted as H_p(d). The personal dose equivalent, is the dose equivalent in soft tissue at an appropriate depth, *d*, below a specified point on the body [67].

The unit of personal dose equivalent is joule per kilogram ($J.kg^{-1}$) and its special name is sievert (Sv). For assessment of the radiation protection quantities 'effective dose', a depth $d = 10$ mm is selected, and for assessing the equivalent dose to the skin, hands, wrists, and feet, a depth $d = 0.07$ mm is recommended. In special cases of monitoring the dose to the lens of the eye, a depth $d = 3$ mm has been proposed to be most appropriate.

3.5 Relationships between quantities

The relationship between the three sets of quantities (physical, protection, and operational) are obviously complex [68]. Therefore, a Joint Task Group representing the ICRP and ICRU was established to conduct a comprehensive review of this relationship, with emphasis on the use of the operational quantities as a valid estimate of the protection quantities for demonstration of compliance with the dose limits. The relationships between the basic physical quantities, the protection quantities and the operational quantities, as shown in Figure (5), [68], and as summarized in Table (3), [15].

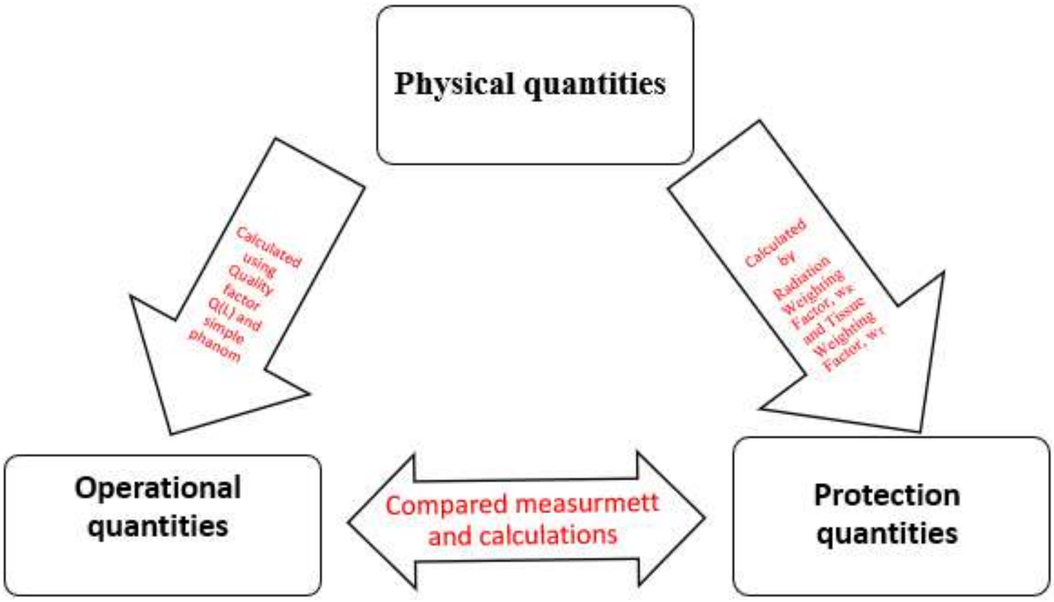

Figure (5): Relationships between the physical quantities, the protection quantities and the operational quantities.

Table (3): Summary of protection and operational quantities and the recommended dose limits.

External radiation	Protection quantities	Operational quantities		Occupational limit	Public limit
		Individual monitoring	Area monitoring		
Strongly penetrating radiation	Effective dose	Personal dose equivalent, $H_{\mathrm{p}}(10)$	Ambient dose equivalent, $H^{*}(10)$	20 mSv/year on average 5 years	1 mSv/year on average 5 years
Weakly penetrating radiation	Equivalent dose to the lens of the eye	Personal dose equivalent, $H_{\mathrm{p}}(3)$	Directional dose equivalent, $H'(3, \Omega)$	20 mSv/year	15 mSv/year
	Equivalent dose to local Skin	Personal dose equivalent, $H_{\mathrm{p}}(0,07)$	Directional dose equivalent, $H'(0.07, \Omega)$	500 mSv/year	50 mSv/year

Together with the basic quantities, there are two types of quantities defined for specific use in radiological protection: protection quantities (defined by the ICRP and used for assessing the exposure limits) and operational quantities (defined by the ICRU and intended to provide a reasonable estimate for the protection quantities).

3.6 A new definition of the operational quantities

In the 2020 year, the ICRU-95 report, [19] recommends an alternative approach to the definition of operational quantities, which is based on the same phantoms as the definition of the protection quantities, which makes them, by definition, good estimators of protection quantities. The ICRU-95 introduces the new quantities and gives conversion coefficients for a wide range of particles and energies, including for the first time, particles occurring only in high-energy radiation fields [19]. Table (4) summarizes the operational quantities by ICRU-39/51 reports [22], [24] and the operational quantities by ICRU-95 report [19].

Table (4): Summary of the operational quantities by ICRU-39/51 reports and the operational quantities by ICRU-95 report.

Protection quantities		The Operational quantities by ICRU-39/51 reports		The operational quantities by ICRU-95 report	
		Individual monitoring	Area monitoring	Individual monitoring	Area monitoring
Whole body	Effective dose	Personal dose equivalent, $H_{\mathrm{p}}(10)$	Ambient dose equivalent, $H^{*}(10)$	Personal dose, H_{p}	Ambient dose, H^{*}
Lens of the eye	Equivalent dose to the lens of the eye	Personal dose equivalent, $H_{\mathrm{p}}(3)$	Directional dose equivalent, $H'(3, \Omega)$	Personal absorbed dose, $D_{\mathrm{p,\ lens}}$	Directional absorbed dose, $D'_{\mathrm{lens}}(\Omega)$
Local skins	Equivalent dose to local Skin	Personal dose equivalent, $H_{\mathrm{p}}(0,07)$	Directional dose equivalent, $H'(0.07, \Omega)$	Personal absorbed dose, $D_{\mathrm{p,\ local\ skins}}$	Directional absorbed dose, $D'_{\mathrm{local\ skin}}(\Omega)$

Table (5) summarizes the phantoms employed to calculate the conversion coefficients from field quantities (Flounce and Air Kerma) to protection quantities and recommended operational quantities [19], [22], [24].

Table (5): Phantoms employed to calculate the conversion coefficients from field quantities (Flounce and air Kerma) to protection quantities and operational quantities.

Protection quantities		The operational quantities by ICRU-39/51 reports		The operational quantities by ICRU-95 report [19]	
		Individual monitoring	Area monitoring	Individual monitoring	Area monitoring
Whole body	Whole-body ICRP/ICRU adult reference phantoms [63]	Slab phantom 300 mm × 300 mm × 150 mm	-ICRU sphere, 300 mm	Whole-body ICRP/ICRU adult reference phantoms	Whole-body ICRP/ICRU adult reference phantoms
Lens of the eye	Eye model embedded in whole-body phantom [69]	Cylinder phantom 200 mm × 200 mm	-Slab phantom 300 mm × 300 mm × 150 mm	Eye model embedded in whole-body phantom	Eye model embedded in whole-body phantom
Local skins	100 mm × 100 mm × 100 mm skin tissue phantom [15]	-Slab phantom 300 mm× 300 mm × 150 mm -Pillar phantom 73 mm × 300 mm -Rod phantom 19 mm × 300 mm	-Slab phantom 300 mm × 300 mm × 150 mm	-Slab phantom: 300 mm × 300 mm × 148 mm ICRU tissue, the front surface of which is covered with 2 mm skin -Pillar phantom:69 mm×300 mm ICRU tissue, cylindrical surface covered with 2 mm ICRP skin -Rod phantom: 5 mm×300 mm ICRU tissue, cylindrical surface covered with 2 mm ICRP skin	Slab phantom 300 mm × 300 mm × 148 mm ICRU tissue, the front surface of which is covered with 2 mm skin

4.7 Comparison among the quantities

The protection quantities are defined for the particle's incidence in the medium in which the body or phantom is located, while operational quantities are defined at the point at which the phantom is located [15]. Two types of quantities are specifically defined for use in radiological protection: protection and operational quantities.

Protection quantities:

- calculated in human phantoms
- realistic dose in a person
- can't be measured
- Dose limits are fixed

Operational quantities:

- calculated in hypothetical
- estimate of dose in a person
- can be measured

- Dose limits are supervised.

3.8 Conversion coefficients

The fundamental characteristic of the protection quantities equivalent dose and effective dose are that they are only calculable (not measurable). The protection quantities values are determined using their relationship to physical radiation field quantities such as particle flounce or air Kerma [15].

The conversion coefficient helps us to determine the risk or the biological nuisance that can result from external exposures. Conversion coefficients relate the physical quantities (flounce and air Kerma) to the operational quantities [10]. Conversion coefficients defined for Reference Person provide numerical links between radiation protection and physical field quantities. Consequently, it is important that ICRP/ICRU reference conversion coefficients are available for general use in radiological protection practice for occupational exposures. To determine the protection quantities and operational quantities, conversion coefficients from physical quantities are needed [70].

Two types of conversion coefficient are of importance, the air Kerma (K_{air}) to dose equivalent conversion coefficient for photon radiation in a unit (Sv/Gy) and the flounce to dose equivalent conversion coefficient for electrons, positrons, and neutron radiation in a unit (pSv.cm^2) [46]. The conversion coefficients have been calculated in two terms for photons: the Absorbed Dose (AD) and the Kerma Approximation (KA). The conversion coefficients obtained represent the reference values to determine the risk that can result from external exposures [15]. The conversion coefficients provide numerical links between these quantities. An internationally agreed set of conversion coefficients must be available which can be generally used in radiological protection practice in situations of occupational exposures and exposures of the public [71]. The latest numerical values of conversion coefficients have been published in ICRU-95 report.

4. Conclusions

The use of a definition of an operational quantity based on a value of radiometric or dosimetric quantities at a point and a conversion coefficient to a protection quantity has been investigated previously. This approach is now considered acceptable, as the International Commission on Radiological Protection (ICRP) has defined effective dose in reference computational phantoms that have published conversion coefficients from particle flounce to this quantity. Effective dose is a universal risk-related quantity for control and optimization of exposures. It is applicable to both external and internal exposure and to all types of ionizing radiations. The drawback is that an effective dose cannot be measured as it is defined as a weighted average over radiation types, organs, and tissues occupying the volume of the human body. Further protection quantities are introduced for the assessment of dose to specific organs, the lens of the eye, extremities, and local skin, and possible targets of deterministic effects of ionizing radiation.

The operational quantities are measurable quantities for the determination of ionizing radiation defined at a point in space. The recommendations in this Report on operational quantities are defined in terms of conversion coefficients to personal dose, personal absorbed dose to the lens of the eye, and personal absorbed dose to local skin; ambient dose, directional absorbed dose in the lens of the eye, and directional absorbed dose in local skin; that are related directly to the values of the protection quantities, and effective dose and absorbed dose in the lens of the eye and local skin. This is a significant change from the ICRU Report 39/51, where numerical values of the operational quantities are based on dose equivalent at a fixed depth in simple phantoms or the ICRU 4-element sphere, and will give a better estimate of the protection quantities. The system of protection and operational quantities is simplified and assists in the comprehension and consistency of radiation protection quantities by users. This research presented a summary of the latest findings of studies and reports of definitions and phantoms for protection and operational quantities. This study aims to define the radiometric quantities, dosimetric quantities, protection quantities, and operational quantities and to compare them. These quantities have an important role in reducing and assessing exposures for workers medically, industrially, and in research in procedures resulting in potentially large doses. The operational quantities are considered the basis of the research in radiation protection in the radiation and Nuclear Systems. The study of comparison between protection and operational quantities is useful to improve standards of protection for workers in procedures resulting in potentially high exposures in complex radiation fields, such as interventional radiology, nuclear medicine, and new developments in the medical, industrial, and scientific research fields.

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