Doc. Ing. Jozef Sabol, DrSc.[1]

Problems of Correct Use of Quantities in Radiation Protection in Assessing the Radiological Threat

Abstract

The paper discusses some difficulties in the use and interpretation of the many quantities introduced for stochastic effects and emphasizes some errors in interpreting these quantities, including the use of operational quantities such as the ambient dose equivalent. Since there is no general quantity for the estimation of deterministic effects where the type of ionizing radiations and exposed tissues or organs have to be taken into consideration, a new quantity – the deterministic effective dose – as a complementary quantity to the present effective dose reflecting stochastic effects has been proposed. In addition, a reduction in the number of quantities currently in use in radiation protection is suggested in order to simplify their use in the regulatory control of radiation exposure in practice involving various radiation or nuclear based applications.

Keywords

Quantity, unit, radiation protection, biological effects

Introduction

The aim of having quantities and units in radiation protection is to quantify biological effects resulting from the exposure of persons to ionizing radiation. These effects include stochastic effects which occur in exposed groups of individuals at low doses with certain probability, and deterministic effects which affect more or less instantly exposed persons as long as their doses are above certain levels or thresholds (ICRP 2007). There are about 10 quantities for the assessment of stochastic effects with the main quantity now being the effective dose, which cannot be measured directly and therefore one has to monitor other quantities and only then express the results in terms of this principal quantity which serves as a quantity for the expression of dose limits, dose constraints and other levels required for controlling radiation exposure in order to meet relevant regulatory requirements. There is no such unified quantity for the quantification of deterministic effects.

The history of radiation dosimetry quantities spans more than 80 years old. After some preliminary efforts, perhaps the first rigorous attempt was related to the definition of the quantity the exposure, which was limited to expressing ionization effects of photons in the air at the point of interest. The use of the exposure has always been complicated by many problems,

[1] jozef.sabol@gmail.com

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Lamačova 825/11, 152 00 Praha 5, http://ochab.ezin.cz, ochab@email.cz

mainly how to satisfy the definition requirements for its accurate measurement. Despite these difficulties, this quantity has played a remarkable role and was used by many generations of health physicists.

In the case of the exposure, as was also the case for the SI System of Unit at that time, in the past the approach was characterized by defining first a unit rather than a quantity (Fig. 1). Today, it is a quantity which is defined first and then an appropriate unit is attributed to that quantity. Since in radiation protection there have been too many quantities introduced, many of them are expressed using the same units and that complicates the situation; on a number of occasions we have information given in a unit but it is not always clear which quantity this unit belongs to. Now, all in all, there is a clear understanding of the difference between a quantity and a unit (Fig. 2).

Later, a more general quantity also suitable for other types of radiations including neutrons was introduced. This quantity – the absorbed dose – was based on the energy imparted by radiation per mass unit of any material. For the purpose of the assessment of biological effects this material was the tissue or tissue equivalent substance.

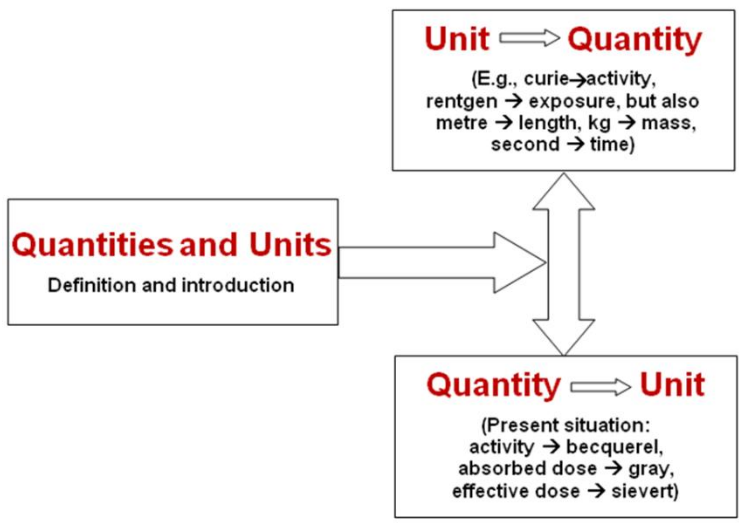

Fig. 1 An illustration of the relationship between a quantity and a unit.

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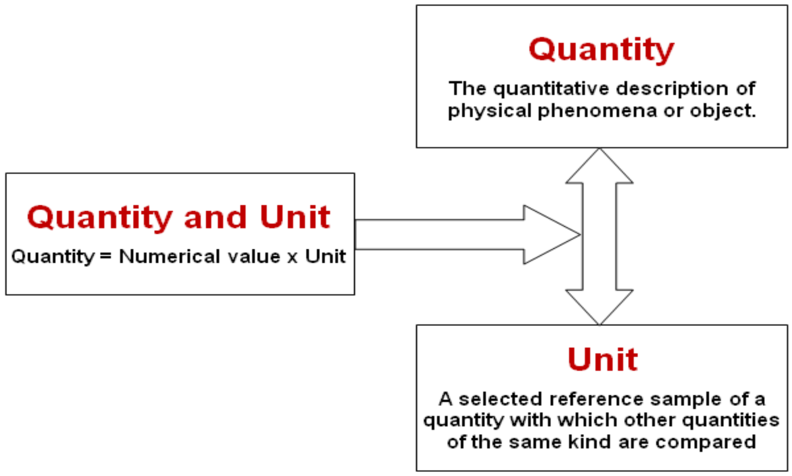

Fig. 2 A current concept of a quantity and a unit.

It was soon recognized that pure physical quantities such as the exposure and the absorbed dose (or simply the dose) appeared to be insufficient to reflect both stochastic and non-stochastic (now called deterministic) effects, and therefore some weighting factors or coefficients were introduced. This resulted in the introduction of too many different quantities with weighting factors which changed quite often depending on our knowledge of the interrelationship between the physical quantities and the biological response of a living body or its organs/tissues.

For obvious reasons, since planned or normal situations prevailed (with low level of exposure), attention was mainly paid to developing quantities for the assessment of stochastic effects. Much less consideration was focused on the development of a parallel system for the quantification of the effects occurring at high doses.

Another aspect related to quantities relies of their means of reflecting the phenomena or properties of the matter being measured. In principle, there are two types of quantities used in the various branches of science, technology and medicine, namely non-stochastic quantities and stochastic quantities (Fig. 3). Unfortunately, in their definitions a clear indication whether the parameters involved are average values or individual observed values showing certain probability distributions is quite often omitted (Sabol 1995).

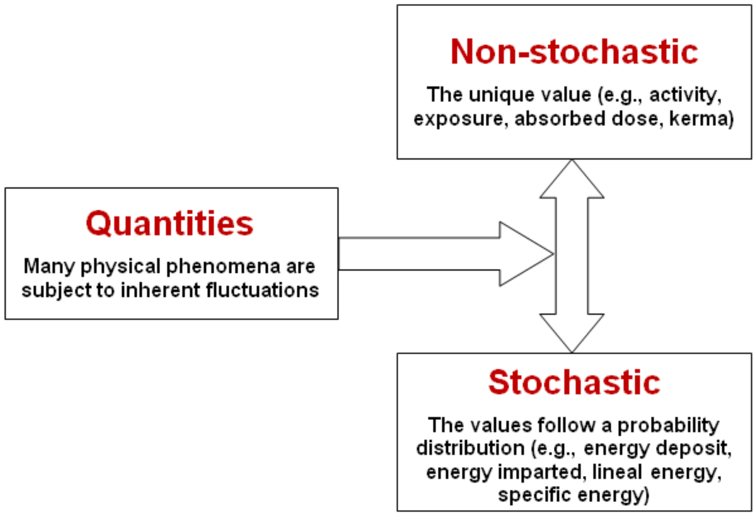

Fig. 3 Non-stochastic and stochastic quantities used in radiation physics, dosimetry, microdosimetry and radiation protection.

Brief history of attempts to quantify radiation, its sources and radiation exposure

It is amazing how pioneers studying radiation and radioactivity were able to make use of very primitive instrumentation for their remarkable discoveries. In fact only very few measuring tools were at their disposal at that time – photographic plates, leaf electroscopes, spinthariscopes and perhaps chemical colour change.

We may summarize here at least some of those milestones which played decisive roles in the atomic age towards the end of the 19th and the beginning of the 20th centuries:

1895 – discovery of X rays (W.K. Roentgen), 1896 – discovery of radioactivity (H. Becquerel), gold leaf electroscope used to make ionization measurements, 1897 – air thermometer used to measure energy transfer by X-rays, 1898 – word “radioactivity” coined and radium discovered (P. and M. Curie);

1903 – spinthariscope as the first direct reading radiation instrument used, 1905 – radiation unit based on ionization first proposed, 1907 – photographic plate carried in pocket for monitoring X-ray exposure, 1911 – international radium standard and curie unit introduced (M. Curie);

1922 – film badges for personnel monitoring, 1925 – first “tolerance dose” proposed, 1928 – roentgen unit formally adopted, International X-Ray and Radium Protection Committee (ICXRP) formed (forerunner of ICRP), 1929 – US Advisory Committee on X-Ray and Radium Protection (USACXRP) formed (forerunner of NCRP), first portable survey meter (L.S. Taylor);

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1931 – USACXRP recommends 0.2 R/d, 1934 – ICXRP recommends 0.1 R/d and 0.5 R/wk, 1936 – USACXRP recommends 0.1 R/d;

1941 – USACXRP recommends adoption of maximum body burden of 0.1 μCi for radium, suggested maximum permissible dose of 0.02 R/d, 1944 – maximum permissible concentration for inhaled radioactivity introduced, rem and rep introduced, 1948 – maximum permissible dose 0.3 R/wk;

1950 - maximum permissible dose 0.3 rem/wk, 1953 – ICRU introduces concept of absorbed dose, rad redefined as the absorption of 100 ergs of energy absorbed in one gram, 1956 – ICRP recommends annual dose limit 40 mSv for workers and 5 mSv for the public, 1960 – annual public limit of 1.5 mSv introduced (continuous exposure), 1962 – ICRU proposes dose equivalent, 1968 - annual public limit of 1.5 mSv introduced, 1974 – gray (Gy) unit adopted,

1975 – becquerel (Bq) unit adopted, 1976 – ICRU introduces dose equivalent, 1977 – ICRP for the first time quantifies the risk due to stochastic effects, ICRP adopts the effective dose equivalent and committed effective dose equivalent, 1979 – sievert (Sv) unit adopted;

1991 – ICRP adopts the effective dose, annual occupational limit 20 mSv (100 mSv for 5 years) and 1 mSv for the public, 1993 – ICRU adopts operational quantities for the assessment of external exposure, 1993 – ICRP redefines effective dose equivalent as the effective dose, ICRP – proposes the RBE weighted absorbed dose with a unit of Gy-Eq.

Too many quantities for stochastic effects

During the recent 40 years or so information about the relationship between radiation physics and dosimetry quantities and the resulting biological effects went through continuously innovating stages aimed at finding the best approach for expressing the consequences following radiation exposure. This lead to the introduction of many new quantities, some of which were modified using new conversion or weighting factors which reflected the results of radiobiology research and the results of intensive epidemiological studies. On the other hand, however, the number of units stayed more or less the same and so several quantities share the same unit (Fig. 4).

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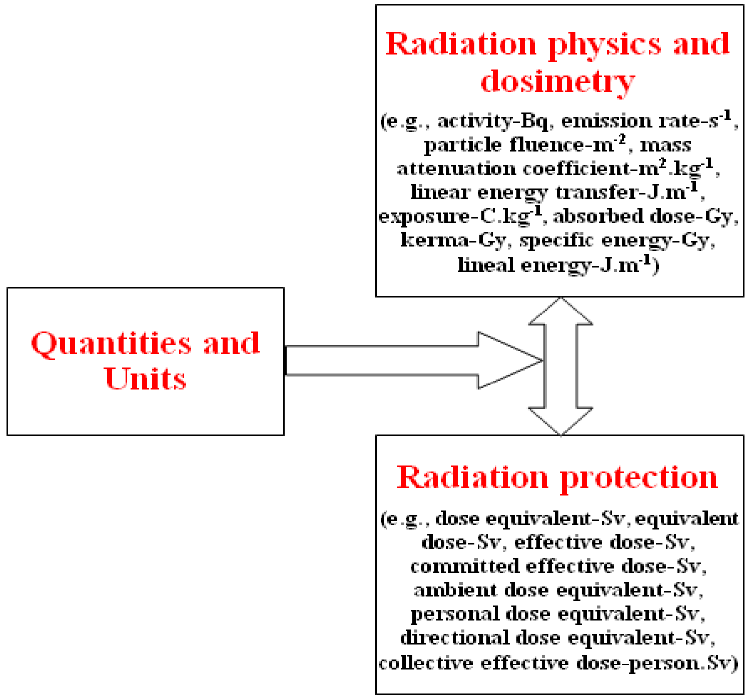

Fig. 4 Too many quantities and not so many units.

Confusion arises in particular with the quantity dose or dose rate which, on a number of occasions, is expressed in units of Sv or Sv/h, but it is rather difficult to recognize what quantity is actually meant (it may be the dose equivalent, equivalent dose, ambient dose equivalent, effective dose or even absorbed dose itself). One of the main problems with this situation is ambiguity in the interpretation of data where the results are given in units but it is not always clear which quantity they represent.

While we have a relatively well developed system of quantities for the assessment of stochastic effects due to exposure from external radiations, measurement and monitoring regarding internal exposure is more difficult since there are no direct operational quantities (ICRU 1993) for the approximation of the main quantity in use in radiation protection – the effective dose (Table 1).

Table 1 Quantification of exposure due to external radiation and internal contamination via the inhalation or ingestion of radionuclides (there are no direct operational quantities for the assessment of internal exposure, which can be measured only through activity concentration in air and foodstuffs or by the measurement of body activity using a whole-body counter or bioassay analysis.

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<table>
<tr><th colspan="2" rowspan="2">Exposure (irradiation)</th><th rowspan="2">Type of control</th><th colspan="3">Operational quantities</th></tr>
<tr><th>Area monitoring</th><th colspan="2">Individual monitoring</th></tr>
<tr><td colspan="2" rowspan="2">External</td><td>Control of effective dose</td><td>$H^*(10)$</td><td colspan="2">$H_p(10)$</td></tr>
<tr><td>Control of dose to the skin, lens, extremities</td><td>$H'(0.07)$</td><td colspan="2">$H_p(0.07)$</td></tr>
<tr><td rowspan="2">Internal</td><td>Inhalation (workers and population)</td><td>Control of committed effective dose (equivalent dose)</td><td>Radionuclide concentration in air</td><td>Inhaled activity (air samplers)</td><td>Body counters, bio-samples</td></tr>
<tr><td>Ingestion (population)</td><td>Control of committed effective dose (equivalent dose)</td><td>Foodstuff activity concentration</td><td>-</td><td>Body counters, bio-samples</td></tr>
</table>

Too few quantities for deterministic effects

In most practical applications of radiation and nuclear technology as well as in other situations where real or potential exposure may be encountered, the problem of monitoring and measurement is virtually reduced to the assessment of comparatively low radiation exposures. Only on rather rare occasions one has to deal with higher doses where deterministic effects may occur. It is no wonder that we now have far more quantities for the evaluation of stochastic effects than for deterministic effects. Moreover, the regulatory requirements presume that the doses will be kept not only below dose limits and dose constraints but as low as reasonably achievable taking into consideration social and economic aspects (ALARA, a well know principle of radiation protection).

The present situation is illustrated in Fig. 5 where the flow chart shows the interrelationships among the basic and derived quantities used for the estimation of stochastic and deterministic effects (IAEA 2011). Whereas the stochastic effects are expressed by means of four quantities (personal dose equivalent, ambient dose equivalent, effective dose and equivalent dose), assessment of the deterministic effects is restricted to only one quantity which corresponds to exposure to individual tissues or organs. There is no unified quantity expressing whole body exposure, where more organs or tissues are exposed to doses exceeding the relevant threshold levels.

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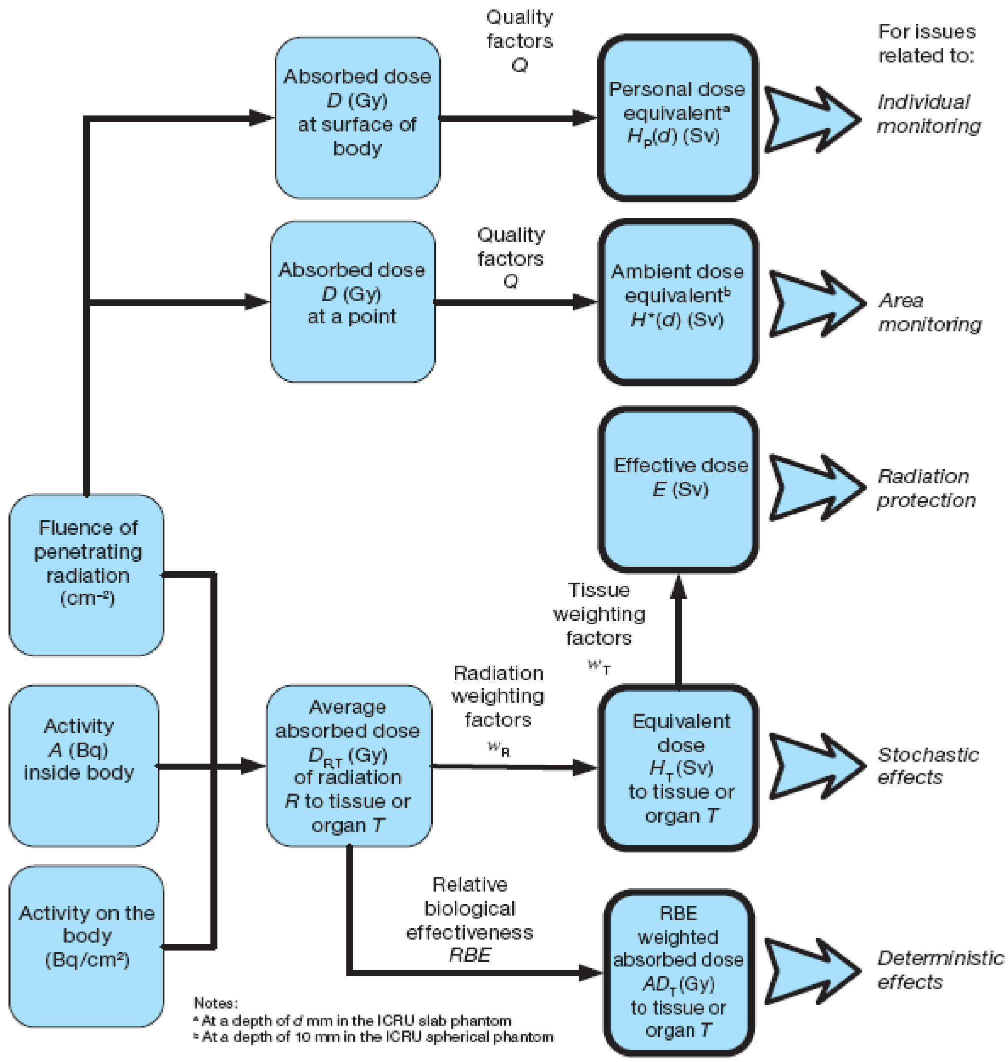

Fig. 5 Main dosimetry and radiation protection quantities showing that the monitoring methods for external radiation exposure are not comparable to those for the assessment of internal exposure (IAEA 2011).

In addition to the illustration in Fig. 5, radiation protection quantities recommended for use in emergency situations are shown in Table 2 (IAEA 2011). Again, also here one has to be careful with the use of quantities designed to reflect stochastic effects for the assessment of deterministic effects.

For the evaluation of deterministic effects we can use either the absorbed dose or, preferably, the RBE weighted absorbed dose with the specification of a tissue or an organ which has been affected by exposure above the relevant threshold (Table 3).

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Table 2 Quantities for the assessment of external and internal exposure where presumably only the quantity RBE weighted absorbed dose can be used for higher exposure associated with emergency situations (IAEA 2011).

Dosimetric quantity	Symbol	Purpose
		Radiation protection quantities
RBE weighted absorbed dose	AD_T	For evaluating deterministic effects induced as a result of exposure of an organ or tissue
Equivalent dose	H_T	For evaluating stochastic effects induced as a result of exposure of an organ or tissue
Effective dose	E	For evaluating detriment related to the occurrence of stochastic effects in an exposed population
		Operational quantities
Personal dose equivalent	$H_P(d)$	For monitoring external exposure of an individual
Ambient dose equivalent	$H^*(d)$	For monitoring a radiation field at the site of an emergency

Table 3 Generic criteria for acute RBE weighted absorbed doses for which protective or other response actions have to be taken in order to avoid or to minimize severe deterministic effects.

Generic criteria		Examples of protective actions and other response actions
External acute exposure (<10 hours)		If the dose is projected: — Take precautionary urgent protective actions immediately (even under difficult conditions) to keep doses below the generic criteria — Provide public information and warnings — Carry out urgent decontamination
$AD_{\text{Red marrow}}$	1 Gy	
AD_{Fetus}	0.1 Gy	
AD_{Tissue}	25 Gy at 0.5 cm	
AD_{Skin}	10 Gy to 100 cm^2	
Internal exposure from acute intake (Δ = 30 days)		If the dose has been received: — Perform immediate medical examination, consultation and indicated medical treatment — Carry out contamination control — Carry out immediate decorporation (if applicable) — Carry out registration for long term health monitoring (medical follow-up) — Provide comprehensive psychological counselling
$AD(\Delta)_{\text{Red marrow}}$	0.2 Gy for radionuclides with $Z \geq 90$ 2 Gy for radionuclides with $Z \leq 89$	
$AD(\Delta)_{\text{Thyroid}}$	2 Gy	
$AD(\Delta)_{\text{Lung}}$	30 Gy	
$AD(\Delta)_{\text{Colon}}$	20 Gy	
$AD(\Delta')_{\text{Fetus}}$	0.1 Gy	

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Current problems and possible solutions

Obviously there is nothing like an ideal system of radiation protection quantities and units. In addition to some definitions there are also difficulties in the interpretation of these quantities and their correct use and interpretation. However, we have to try to make it as comprehensive and reliable as possible to serve the purpose of radiation protection under the circumstances. Some of the problems we encounter both in the use of the present system and some of its deficiencies and imperfections may be presented as follows:

- A unit (e.g., Gy, Sv, Bq is given but not the quantity or radionuclide to which it is related),
- The quantity exposure is used for high energy photons for which this quantity has no meaning because of its definition,
- The distinction between non-stochastic and stochastic quantities is sometimes ignored,
- The dose is often given in Sv and it is not always clear to which quantity this unit is related,
- The radiation level is often presented in Sv/h although the radiation level is not a recognized quantity,
- The measuring range of instruments is occasionally given in such a form as e.g., 0-10 Sv, which may create a false feeling that the instrument can measure the quantity involved virtually from zero up (moreover, since the unit Sv was introduced only for stochastic effects, its use at such high levels may be irrelevant),
- The dose rate on the surface expressed in Sv/h may be questioned,
- The dose equivalent is used instead of the ambient dose equivalent, which is often confused with the equivalent dose,
- The dose at the point of interest (in tissue) cannot be multiplied by weighting factors (in this case the only factor to be used is the quality factor),
- The (absorbed) dose is often used as a universal measure of exposure (irradiation),
- Dose, kerma or exposure at a specific point as a measure of the effective dose is not always correct,
- Confusion among the use of Q, w_R and RBE and their dimensions which should be in units of Sv/Gy (in addition, there is a problem in the values of these factors for high-energy radiation fields),
- Ambiguity and complexity of the present system leads to problems in presenting radiation protection concepts in a clear and understandable way to students, workers and even specialists in the field (this is "supported" by some books and monographs written by specialists in the application of radiation rather than in radiation protection but they usually include a chapter or two presenting radiation protection in an obsolete and unprofessional manner),
- The inappropriate use and interpretation of radiation protection quantities and units is also "maintained" by outdated national legislation in many countries which have not been able to incorporate the latest international recommendations into their laws and regulations,

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- The collection of data by the UNSCEAR about the radiation protection situations in many countries throughout the world may not always be reliable since this information is quite often supplied by officials who have very limited knowledge of radiation protection and especially its quantities (since ICRP often refers to these data, some of its conclusions based on incorrect information may be challenged),
- The number of quantities available for the expression of stochastic effects is greater than the quantities available for deterministic effects where, moreover, there is no unified quantity for assessing whole body deterministic effects.

Based on the above-mentioned facts and my observations as well as experience from visiting hundreds of institutions, laboratories and other workplaces in many countries worldwide where radiation and nuclear technologies were applied in some way, the author believes that the present system of radiation protection quantities and units has to be modified in order to make it more efficient in serving both regulatory control and research.

First of all, it is suggested to focus our attention in the near future on the following issues:

- To retain the present system and continue in its refinement in accordance with the latest radiobiology knowledge and epidemiology results but this system would serve scientific rather than practical purposes (not for routine regulatory control of radiation exposure of workers, patients and population),
- To simplify and convert the present system into a system which can be better understood and applied by all those who work with radiation and who are not always familiar with all those peculiarities of the current complicated structure of sophisticated quantities and units (such a system has to rely only on quantities which can be readily monitored and measured), and
- To introduce a unified quantity for the overall assessment of the deterministic effects in a similar way we have the quantity effective dose for the stochastic effects.

This proposal may be illustrated in Fig. 6 (Sabol 2011a) where the present system is split into two branches, one of which will focus attention on continuing to develop the system further, taking into account all possible information and new knowledge, while the other will concentrate on simplifying the present system (including a reduction in the number of quantities) so that it can be better followed and applied worldwide. Of course, it is presumed that there will be close and coordinated cooperation between scientists and academicians on one side and relevant regulatory authorities and the people in the field on the other side. The simplified system will surely help especially developing as well as developed countries to acquire a unified and consistent system which can be recognized and practiced all over the world. This will certainly contribute to collecting more reliable data about radiation exposure worldwide. At present, the system is being developed mainly by scientists and specialists from highly developed countries who may not always be familiar with the situation and real infrastructure prevailing in many developing countries where they usually cannot implement

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a sophisticated system because of a lack of qualified personnel and resources to acquire expensive instrumentation.

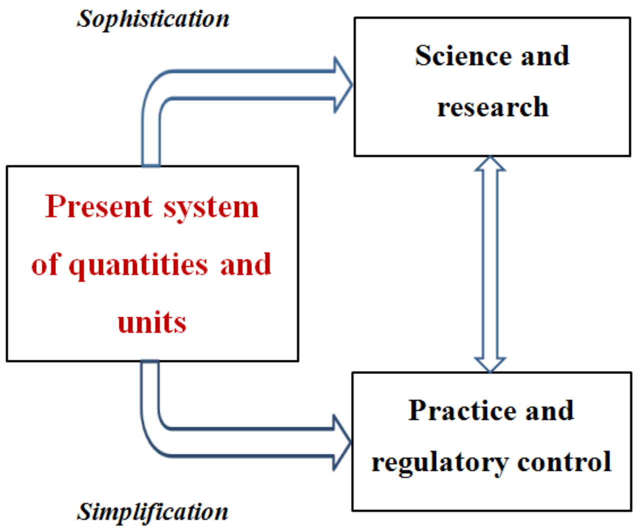

Fig. 6 A possible solution to the problem of too many quantities currently in use in radiation protection.

With respect to radiation protection quantities, the quantity of the effective dose may stay as it is (ICRP 2007). It may be renamed, however, as the stochastic effective dose (E_S)

$$E_S = \sum_T w_T \sum_R D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose in an organ or tissue T, due to radiation of type R, w_R is the radiation weighting factor for radiation R, and w_T is the tissue weighting factor. The unit of this basic dose limit quantity is Sv, which corresponds to a unit of the mean dose Gy (gray) modified by weighting factors which in fact convert a physical quantity—the dose, into a physico-biological quantity—the effective dose.

Alternatively (Sabol 2011b), one may introduce a quantity for the deterministic effects – the deterministic effective dose (E_D), parallel to the effective dose for the assessment of stochastic effects

$$E_D = \sum_T v_T . u_{thr}(D_{DT,thr}) \sum_R v_R D_{T,R} = \sum_T v_T . u_{thr}\big(D_{DT,thr}\big). D_{TD}$$

where $D_{T,R}$ has the same meaning as mentioned in the case of stochastic effects (i.e. the mean absorbed dose in an organ or tissue T, due to radiation of type R), v_R is the deterministic radiation weighting factor for the type of radiation R, $D_{DT,thr}$ is the deterministic equivalent dose

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threshold (for a tissue or organ T), $u_{thr}(D_{TD,thr})$ is a factor which is equal to zero for $D_{TD} < D_{TD,thr}$, while at $D_{TD} \geq D_{TD,thr}$ this factor is equal to one, D_{TD} is the deterministic equivalent dose in a tissue or organ T (a parallel quantity to the equivalent dose in a system of stochastic quantities), and v_T is the deterministic tissue weighting factor the value of which will obviously be related to the RBE of the radiation of the type R.

Conclusion

The protection of persons including radiation workers, patients and members of the public has to rely on a sound system of radiation protection quantities and units which should be defined, introduced and interpreted in such a way as to avoid any ambiguity or confusion. Only such a system can be used to assess and control radiation exposure in both situations: where stochastic and deterministic effects are expected. Obviously, only a generally and internationally recognized system of quantities in this field will provide trustworthy results of monitoring persons; this is important for maintaining their adequate protection as well as for obtaining reliable data for epidemiological studies which may further improve our understanding of biological effects due to radiation.

Up to now, during more than 110 years dealing with radiation and its various sources, we accumulated a tremendous amount of valuable information about the effects of this phenomenon. We can be proud of these achievements because now we know much more about radiation than we know about any other dangerous substances or toxic agents. Moreover, we are able to control radiation levels to a very low exposure comparable or lower than it is natural radiation background. This is partly because we can measure radiation exposure with extremely high sensitivity, which is incomparable with the situation in other areas where we deal with pollutants or other harmful effects. However, in order to maintain and further improve these extremely high standards of protection against ionizing radiation, it is desirable to have appropriate tools, including a transparent system of quantities and units.

This is why it is suggested to look into the matter from the current level of our knowledge and experience in the field and to consider splitting radiation protection quantities into two categories: one, in fact, a continuation and upgrading of the present system (which has become rather complicated for practical use) which would serve research and scientific studies, while introducing another system which would rely on the present system but would be sufficiently simplified in order to be readily used in practice where it is important that all main quantities should be directly measurable.

Another suggestion is related to the adoption of a new unified quantity for assessing overall deterministic biological effects so that such a quantity can be a counterpart to the quantity effective dose developed for the reflection of stochastic effects.

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There are also some other problems we have to address in the future. One concerns the assessment of deterministic effects due to acute inhalation and possibly also for ingestion of radionuclides, which may occur in radiological accidents or other emergency situations including terrorist attacks. The existing conversion factors cannot be used for this purpose since they have been developed only for the evaluation of stochastic effects.

Acknowledgments

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