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QUANTIFICATION OF THE RISK-REFLECTING STOCHASTIC AND DETERMINISTIC RADIATION EFFECTS

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Abstract. *The purpose of radiation protection is to protect workers, patients and members of the general public against any excessive impact of exposure to ionizing radiation, and to control the radioactive contamination of the environment in accordance with the strict regulatory standards. In order to adopt any measures to regulate the exposure from various sources, it is necessary to introduce a reliable and consistent system of the quantification of radiation exposure due to external and internal sources. Only very low doses (comparable with the natural radiation background) are encountered under normal circumstances. Such exposures may result in stochastic (delayed) effects, where the probability of their occurrence is proportional to the magnitude of the effective dose expressed in Sv (sievert). While for the stochastic effects only the unit of Sv can be used, for the quantification of deterministic effects (tissue reaction), which occur at rather higher doses, other quantities and units are more appropriate. In this case, one relies on a new quantity, namely RBE-weighted dose with a unit of Eq-Gy (equivalent gray). The paper offers some original illustrations of the system of quantities for assessing both stochastic and deterministic harmful effects of ionizing radiation.*

Key words**:** *Ionizing radiation, radiation protection, exposure, risk, radiation quantities, stochastic effects, deterministic effects, Sv, Eq-Gy*

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1. INTRODUCTION

Almost any use of radiation or nuclear technologies in industry, medicine and many other fields results in some exposure of workers, members of the public and, in medical applications, also of patients. This exposure is considered undesirable, but one cannot completely eliminate it. Low exposure, however, is related to such a small risk that it can be tolerated against the benefits radiation can provide, especially in medicine, where the positive contribution is much higher than a potential harmful impact.

In any area where the exposure of persons is expected, the main aim of radiation protection is to minimize this exposure to the very minimum while allowing the utilization of the radiation for particular beneficial purposes. In order to control radiation exposure, one has to quantify it; therefore, quantities have been introduced to characterize the biological effects of the exposure that a person incurs. The problem we encounter in this area is due to too many quantities introduced over the past years and, to a certain extent, the units which have been adopted in radiation protection. Moreover, there are quantities which are defined either in a rather complicated manner or their definitions cannot be interpreted unambiguously.

This is why we are experiencing many problems in the measurement of these quantities, where often only approximate results of the quantity in question must be tolerated.

Some old quantities and units still appear in technical and even scientific publications. Many reports are causing a lot of confusion, especially to those who may be experts in using radiation, but may be lacking the up-to-date knowledge in the current radiation protection concepts, including the correct understanding and interpretation of quantities used in the field [1-3]. This is why the community using radiation in a variety of applications has to possess a basic understanding of radiation protection quantities and units, so that they can apply them correctly in line with the relevant national and international safety standards.

2. TOO MANY QUANTITIES AND LACK OF UNITS

Since the discovery of X-rays in 1895 and radioactivity in 1896, there have been many attempts to define and introduce suitable quantities for the assessment of the detrimental effects of ionizing radiation exposure [4, 5]. In addition, the problem is aggravated by too many radiation protection quantities with the same units.

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Soon after these discoveries were made, it was recognized that the exposure to radiation could result in some harmful effects to an exposed person. During the first 50 years or so, numerous cases occurred with visible effects observed on persons working excessively with radiation or radioactive sources. There were also some incidents and accidents involving sources of ionizing radiation. In some circumstances, simple protection measures were introduced only when detrimental health effects were more or less immediately visible. Such injuries were clinically recognizable and attributed to radiation. Concurrently, it was concluded that the severity of the health injuries was related to the magnitude of the exposure. These kinds of the biological effects are now termed as deterministic effects or tissue reactions. They always occur if the dose exceeds a certain threshold value.

On the other hand, later in the 1950s other types of effects were identified, namely stochastic biological effects. These effects appear in exposed persons with a certain probability which is proportional to the effective dose. These effects occur at low exposure, up to about several hundred mSv, while deterministic effects are characterized by a threshold, which for some effects may begin at a dose higher than about 0.5 Gy.

3 Quantities for assessing biological effects from external and internal exposure

In principle, a person can be exposed by external penetrating radiation or through radiation emitted by radionuclides which entered the body. In both cases, the effective dose is used as a measure of stochastic effects, where many relevant factors are taken into account, namely the type of radiation, irradiation geometry and activity of radionuclides inhaled or ingested. The physical as well chemical properties of the radioactive substance which entered the body are also considered.

The main quantities important for assessing the exposure due to external radiation are presented in Figure 1.

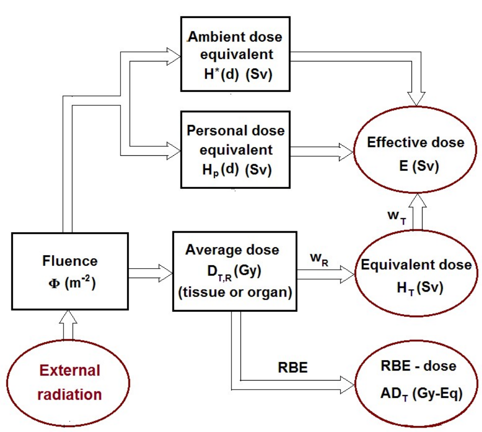

Figure 1. Relations between various radiation protection quantities used to assess stochastic effects following the external exposure (w_R and w_T are the relevant weighting factors)

Since the main quantity – effective dose – cannot be measured directly, operational quantities, such as the ambient and personal dose equivalent, have been introduced to approximate this quantity.

Both quantities, the ambient dose equivalent and the personal dose equivalent, can be used for monitoring of the contribution to the effective dose from penetrating radiation. In addition, both quantities can also be used to assess the exposure to extremities and to the skin. For this purpose, the depth is taken to be 0.07 mm.

The main function of radiation monitors and dosimeters is to check and demonstrate the compliance with regulatory dose limits. These instruments are calibrated on appropriate phantoms in standardized radiation fields in order to yield readings in terms of the operational quantities. The instruments serve as an important indicator of the radiation levels at workplaces and the exposure received by radiation workers monitored by special personal dosimeters. The situation is summarized in Table 1.

Table 1. Operational quantities used for monitoring of workplaces and radiation workers

Control	Purpose of operational quantities	
	Area monitoring	Individual monitoring
Effective dose	$H^*(10)$	$H_p(10)$
Skin dose	$H^*(0.07)$	$H_p(0.07)$

Obviously, there is a fundamental difference between the external and internal exposure. While in the former case a person receives the exposure only during the period of being subjected to the external radiation field, internally deposited radionuclides contribute to the exposure of a person for the time depending on the physical and chemical properties of radioactive materials inhaled or ingested, and a special role is played by the half-life of radionuclides and by the biological removal of the materials from the organs or body.

Both dose limit quantities and operational quantities are quantified in the unit of Sv, which cannot be used for the exposure above a certain threshold level, where only a unit based on the absorbed dose weighted by the RBE (relative biological effectiveness) must be used. This unit, Gy-Eq (gray-equivalent), reflects the deterministic effects to a particular organ or tissue. So far, no quantity similar to the effective dose defined for stochastic effects has been introduced.

As long as a person is radioactively contaminated, the situation may result in the whole-body exposure or exposure of individual organs or tissues (Figure 2). This exposure can be quantified as the committed effective and equivalent dose for stochastic effects and committed RBE-dose to assess the deterministic effects.

Under normal circumstances, when everything goes the way it was planned, we experience only stochastic effects. Higher exposures may occur in the case of radiation or nuclear incidents or accidents. The aim of radiation protection is to be prepared for such occasions and minimize the impact of any emergency situation to the public.

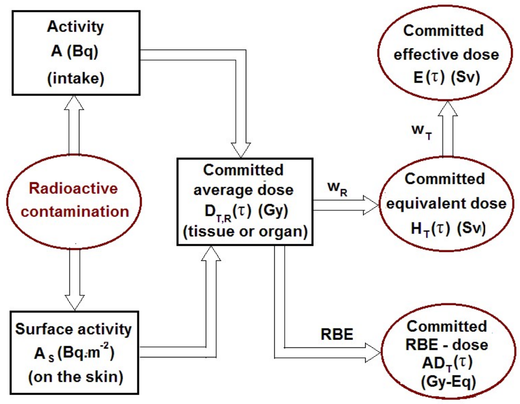

Figure 2. Quantities characterizing personal exposure from the intake of radioactive material or from skin contamination

4. What can be expected from stochastic and deterministic effects

An illustration of the characteristics of the two main biological effects caused by radiation exposure is shown in Figure 3. The effects differ and depend on the probability of occurrence and severity of the exposure.

The relevant risk coefficients have been proposed by the ICRP (Table 2) for stochastic effects. It can be seen that the combined detriment due to excess cancer and hereditary effects is about 5% per Sv. This is the same as $5x10^{-5}$ mSv^{-1}, 5 in 100,000 or 1 in 20 000.

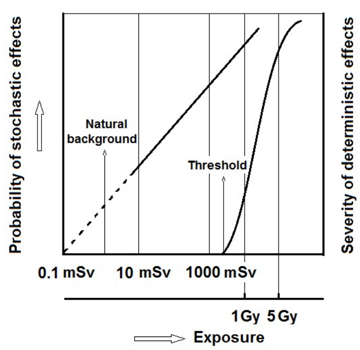

Figure 3. The main difference between the stochastic and deterministic biological effects

Table 2. ICRP detriment-adjusted nominal risk coefficient (10^{-2} Sv^{-1}) for stochastic effects after the exposure to radiation at low doses

Exposed population	Cancer		Hereditary effects		Total	
	2007	1991	2007	1991	2007	1991
Whole	5.5	6.0	0.2	1.3	5.7	7.3
Adult	4.1	4.8	0.1	0.8	4.2	5.6

Deterministic effects have a threshold below which the effect does not occur. The threshold may be very low and may vary from person to person. However, once the threshold has been exceeded, the severity of an effect increases with the dose. The symptoms of a person exposed to high doses together with a proposed treatment are presented in Figure 4.

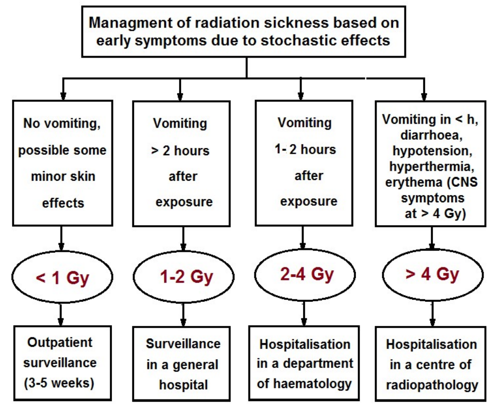

Figure 4. Radiation sickness of persons having received high doses and their management (CNS – Central Nervous System)

5. Some problems with the current radiation protection quantities

Because of different quantities and also units used, it may not be easy to compare the actual levels of exposure or radioactive contamination. This was proved to be the case especially when it comes to the communication of radiation or nuclear risk to members of the public. The problem is caused not only by mixing traditional (old) units with the currently introduced SI units, where there is confusion between Bq and Ci for assessing the activity, and Gy and rad, Sv and rem, which are used in radiation protection. Further confusion may arise from the magnitude of units often expressed using prefixes, which are sometimes necessary since, for example, the unit for the activity (Bq) is too low, while the unit used for the effective dose (Sv) for applications in radiation protection is too large. Table 3 gives an overview of some frequently used prefixes.

Table 3. Prefixes often used with SI and old units

Multiple	Prefix	Symbol	Practical examples
10^{12}	tera	T	44 TBq, activity corresponding to 1 g of radiotherapy source ^{60}Co
10^{9}	giga	G	4 GW, the total electric power of two Czech nuclear power plants
10^{6}	mega	M	1 MBq = 27 µCi
10^{3}	kilo	k	1 nCi = 37 kBq
10^{-3}	mili	m	20 mSv/y, annual dose limit for radiation workers
10^{-6}	micro	µ	4 µSv/h, the effective dose rate airline flight crew receive per hour
10^{-9}	nano	n	100 nSv/h, normal background ambient dose equivalent rate
10^{-12}	piko	p	1-100 pA, current of the ionizing chamber

Numerical mistakes may occur especially in the case of the preparation of radiopharmaceuticals when coming from the unit Ci to Bq. In the case of nuclear accidents, the releases of radioactive materials are sometimes given in the unit TBq or kCi. It may not be easy to convert the radioactive contamination in kBq/km^2 to Ci per square mile and vice versa.

Another peculiarity concerns confusing the conventional unit R (roentgen) for the quantity exposure X where the SI unit is C/kg with the conversion 1 R = $2.58x10^{-4}$ C/kg. Here, one has to realize that the quantity of exposure can only be used for gammas and X-rays in the air, but not for charged particles or neutrons. The old popular approximate relationship 1 R = 1 rad = 1 rem is valid only for photons. Sometimes, the use of the quantity kerma (K) may also be confused when we forget that this quantity in Gy can only be applied to non-directly ionizing radiation (neutron, photons).

There was also a lot of confusion in reporting the radiation situation following the Fukushima nuclear power plant accident. The official authorities released the information about the contamination around the affected site once in $Ci.km^{-2}$ and subsequently in $kBq.km^{-2}$. Here, the difference is very significant indeed, since 1 Ci = $3{,}7 \cdot 10^{10}$Bq. Frequent errors also occurred when reporting the exposure in various units, namely rad , Gy, rem or Sv, where the relationship is 100 rad = 1 Gy and 100 rem = 1 Sv. More difficulties have been encountered when transferring the exposure in R into the absorbed dose in Gy. The exposure in R can only be used as a measure of exposure from photons up to an energy of about 500 keV and only in air (not for beta, alpha or neutrons).

The estimation of risks to human health from the exposure to ionizing radiation is usually based on epidemiological studies where large populations exposed to known doses are compared and analysed with another similar group, which has not been exposed. Based on such evaluation, it would be possible to get relevant information about the mechanisms and processes that play an important role in carcinogenesis after the exposure to ionizing radiation [6].

At present, risk assessment relies on risk coefficients proposed by the ICRP [7]. These coefficients, which are related to the effective dose, are only relevant for stochastic biological effects, i.e., for low-level exposure up to several hundreds of mSv. Statistical inference is critical in characterizing and quantifying uncertainty in both estimation of risk from radiation exposure for specific studies and in projection of risk to other populations and exposure scenarios. At normal occupational levels, the most important effect is the increase in the potential for developing a latent fatal cancer after the exposure to radiation occurs.

Elementary principles for general risk assessment methodology have to take into account special terminology consistent with international standards, e.g., those by the EU [8]:

- *risk*: combination of the probability of occurrence of a hazard generating harm in a given scenario and the severity of that harm;
- *harm*: injury or damage to the health of people;
- *hazard*: potential source of harm;
- *probability of occurrence of harm*: the likelihood of the harm occurring in accordance with the proposed criteria.

In the case of deterministic effects or harmful tissue reactions (which depend not only on the total dose but also on the dose rate), the risk associated with radiation impact cannot be quantified by the same quantities as are used for the assessment of stochastic effects. The general system of quantities for this purpose has not been fully developed for this assessment but there is an attempt to distinguish these two effects by a quantity RBE-weighted dose [9] corresponding to deterministic effects. This quantity is supposed to be an equivalent for the effective dose widely associated with stochastic effects.

7. Conclusion

The reliable assessment of radiation exposure requires a consistent system of clearly defined quantities and the adoption of relevant units. During the last 100 years or so, the progress in radiation protection has been focused on introducing quantities reflecting biological effects, taking scientific and radiobiological findings into account. The approach was modified before adopting a different system of quantities to distinguish between stochastic (delayed) and deterministic (early) effects. Some quantities were introduced and then modified in order to denote a better biological response to radiation exposure (e.g. exposure, absorbed dose). New quantities, such as kerma, dose equivalent, equivalent dose, effective dose, ambient dose equivalent, personal dose equivalent and some others were introduced along with the general progress in this field. No wonder that even experts in the field are sometimes confused. Of course, the media and members of the public have been puzzled by the results associated with radiation situations reported in many different quantities and units. Consequently, the system of quantification of radiation exposure should be simplified and reflect the magnitude of exposure in a more understandable way so that the public can perceive the real hazard in perspective and in comparison with some other hazards they are familiar with.

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