

Review Article

The State of the Art of the World Radioprotection System

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Abstract: Ionizing radiation can expose individuals, and this exposure may cause deleterious biological effects. Protection against these effects, called radioprotection is accomplished through actions at the source, on the exposure routes and on the individual. It is assumed a proportional relationship between increased exposure and increased risk of stochastic effects of exposure. This approach allows dividing the network events and exposure situations and evaluating steps which are important for radioprotection. The aim of this study is to evaluate the state of the art radiation protection recommendations published by the International Commission on Radiological Protection (ICRP). For operational reasons, the radioprotection needs to perform simplifications in the relations between sources and biological effects. The last simplification was made in 2007, dividing the relations according to the sources and individuals. The principles of radioprotection (justification, dose limitation and optimization) were maintained and strengthened. The ratio depending on the source allowed the inclusion in the sources of regulatory framework previously not included and definitions of dose constraint concepts and reference levels. All this, when used with the principle of optimization of radiation protection can restrict individual doses. The maintenance of the three radiation protection principles demonstrates the robustness of these principles, as well as the maintenance of the dose limits demonstrates the confidence of the radioprotection community in the safety of these limits. Brazilian radioprotection did not reach yet the state of the art described here and is still based on ICRP previous recommendation edited in 1990, but being the legal regulations for Brazil they must be obeyed. All legislation based on ICRP No 60 and subsequent recommendations are able to protect quite adequately the environment and workers, although they are not in the state of the art as defined by the ICRP No 103 and subsequent recommendations.

Keywords: Radiation Protection, Radioprotection, Ionizing Radiation, Evolution of Radiation Protection, ICRP

1. Introduction

In November 1895, Roentgen discovered a new kind of radiation, the X-rays. Among other properties, X-rays possessed enough energy to be able to ionize the atoms. A year later, Becquerel discovered the radioactivity of uranium and associated ionizing radiations. Such radiations are a natural phenomenon to which all things and beings are exposed, since the origin of times and life, and this exposition still continues.

Both X-rays and radionuclides produced additional sources of radiation exposure that can cause deleterious effects in organisms. Thus, occupational and medical exposures in addition to natural exposure have generated a framework of increased risk. Another factor of increased risk was the preparation of new radionuclides, called artificial radionuclides.

Protection from deleterious effects caused by ionizing radiation appeared to be a need. This is the role of

radioprotection. Since its creation a century ago, radioprotection has had a consistent evolution starting from considerations focused on some aspects of occupational exposure and medical recommendations, then including all forms of medical and occupational exposure and finally the current recommendations that include all forms of exposures, in addition to the occupational and medical ones. The present study aims to describe the state of the art of radiation protection.

2. Evolution of the Radioprotection

The evolution of radioprotection can be seen on other aspects, such as the scope of radiation protection, the ethical basis of protection and the protection method, as can be seen in Table 1.

Table 1. Evolution along time of the ICRP recommendations, following ICRP 109 [1].

Factor analyzed	Early recommendations	Intermediate recommendations	Present recommendations
Circumstances of exposure Considered	Occupational exposure in medicine	First, all occupational exposure, then all exposure of mankind	All exposure of all species
Who/what is being protected	Protection of man alone	Environment assumed protected because man is protected	Demonstration that environment is protected
Known effects of radiation exposure, aims of radiological protection	Prevent deterministic effects...	... and avoid stochastic effects...	... and recognize the possibility of non-target effects
The ethical basis of protection	Respect for life virtue ethics	Focus on utilitarian ethics	Increasing emphasis on deontological ethics
Protection methods	Advice on practical protection methods	Application of dose limits, then application of optimization	Optimization of protection under dose and risk constrains

The first recommendation of ICRP on the use of the concept of dose was made in 1930 in London. The dose was given by the exposure expressed in the unit "Roentgen" multiplied by a correction factor depending on the kind of radiation. The unit to express the dose was the "Roentgen Equivalent Man" (rem) and the proposed dose limit for exposure to X-rays was fixed at 0.2 rem per day [4].

In 1950, the ICRP, which remained off during Second World War, was rebuilt and altered the previous recommendation that fixed the maximum permissible dose per day at 0.2 rem·d⁻¹ to a maximum permissible dose per week equal to 0.3 rem·w⁻¹ [3].

In 1955, the first publication of the ICRP was edited, as the supplement number six of the "British Journal of Radiology." This publication was born at the meeting of the ICPR in 1953, and further revised in 1954 [3].

In its publication No 1 released in 1957 (ICRP-1), the ICRP abandoned the dose limit per week and proposed an annual dose limit. Originally the proposal was to calculate such annual dose limit from the weekly dose limit established in 1950 (0.3 rem), multiplying this value by 50 (number of weeks per year) and obtaining then the maximum annual dose equal to 15 rem. However, this limit was strongly questioned in terms of its safety, mainly considering genetic effects regarded as having no threshold dose for the induction of leukemia [3].

Recommendations of the ICRP-1 suffered relevant changes only in 1965 (ICRP No 9), when the concept of stochastic biological effects of ionizing radiation was definitely accepted. Thus, ICRP-9 stated that "*any exposure may involve some*

In Brazil, radioprotection is defined by norm CNEN-NN-3.01 [2] a set of measures intended to protect the human being and its descendants against eventual unwanted effects caused by ionizing radiation. Lindell attributes to the American engineer Wolfram Fuchs the first systematization of these procedures that were published on December 12, 1896 [3], a bit more than one year after Roentgen's discovery of X-rays on November 8, 1895. Following Lindell [3], in Fuchs's recommendations the focus was a deterministic effect: the erythema. The recommendations were: "*1) make the exposure as short as possible (control of time); 2) do not stand within 12 inches (30 cm) of the X-ray tube (control of distance); and 3) coat the skin with Vaseline (a petroleum jelly) and leave an extra layer on the most exposed area*". Afterwards, major milestones of radioprotection were the creation of the ICRP in 1925, the UNSCEAR in 1956, and the IAEA in 1957 [4].

degree of risk, the commission recommends that any unnecessary exposure should be avoided, and that all doses should be kept as low as readily achievable, economic and social consequences being taken into account." Nowadays, this concept is known by the acronym ALARA that means "As Low As Reasonably Achievable" [4].

In 1974, the ICRP started to review its recommendation No 9, making several important changes, such as abandoning the concept of critical organ. The accumulation of knowledge about the risk of cancer in various organs allowed the development of a new quantity based on a weighting factor for the entire body of the biological effects of ionizing radiation in different organs. In 1978, this quantity was called "Effective Equivalent Dose" [4].

In 1977, there was a major change in radiological protection, with the ICRP publication No. 26. The concept of detriment was introduced and the of dose unit "Roentgen Equivalent Men" (rem), was replaced by the new unit, "Sievert" (Sv, with 1 Sv = 100 rem = 1 J·kg⁻¹). The cost-benefit ratio was consolidated in radiological protection. The justification of the practice, the optimization of radiological protection and the limitation of individual dose became the basic principles of modern radiation protection. The value of the annual dose limit, introduced in 1957, was reduced from 15 rem·y⁻¹ to 5 rem·y⁻¹ or 50 mSv·y⁻¹, and the limit for an individual of the public was lowered from 0.5 rem·y⁻¹ to 0.1 rem·y⁻¹ or 1 mSv·y⁻¹ [3].

In 1987, the ICRP-26 was revised by a working group specially created for that purpose. This resulted, in 1990, in the

release of the ICRP-60, a publication that made significant changes in the concepts of radiation protection. Thus, the occupational exposure limit was reduced from 50 to 20 mSv·y⁻¹ (calculated as the average over 5 years) and the exposure of the public continued at 1 mSv·y⁻¹ (5 years average). The evolution of the dose rate limit values can be seen in Table 2. Reference was made to exposure to natural sources. The document also

established the distinction between practice (that is when doses are introduced) and intervention (when doses are reduced) and finally introduced the concept of constraint. Minor changes were the substitution of the weight factor Q by w_r and the replacement of the expressions “equivalent dose” and “effective equivalent dose” respectively by “dose equivalent” and “effective dose equivalent” [5].

Table 2. Evolution of the dose limit values.

Date	Unit	Original dose limit	Dose limit per year (m Sv·y ⁻¹)	Percentage of the highest value	Ref.
1930	rem	0.2 d ⁻¹	730	100%	[3]
1950	rem	0.3 w ⁻¹	150	21%	[3]
1977	mSv	50 y ⁻¹	50	15%	[7]
1990	mSv	20 y ⁻¹	20	2, 7%	[5]
2007	mSv	20 y ⁻¹	20	2, 7%	[4]

d = day, w = week, y = year; conversion factor: 1 mSv = 0.1 rem.

The last major change in radiation protection occurred in 2007, when the ICRP published a recommendation that defined the state of the art of the radiation protection system [4].

3. The State of Art of Radioprotection

3.1. Principle of Application of Dose Limits and the Linear No Threshold Model

The principle of application of dose limits is individual-related and applies in planned exposure situations. The risk-based radiation protection proposed by ICRP is focused on the linear no threshold hypothesis (LNT), which assumes proportionality between radiation dose and risk due this dose [5-6]. This theory is used in low dose situation (below 100 mSv·y⁻¹) [4-6]. In this case, the risk considered is the increment in the probability of incurring cancer or heritable effects. The use of this model presupposes that a single interaction of radiation with living matter can cause deleterious biological effect. With increasing number of interactions of radiation with matter, the risks increase proportionally. The stochastic feature of the expression of biological effect of radiation in low doses associated with LNT models make it impossible to distinguish between safe and dangerous, but allows us to establish limits of acceptable risk, below which risk can be considered contemptible [5].

There are several biological evidences supporting the LNT model as one refers to DNA damage induced by ionizing radiation. In some cases, mechanisms for damage repair in mammalian species tend to point to the possibility that a threshold for cancer induction cannot be ruled out at low dose, but this threshold cannot be determined with current knowledge [4].

Increased knowledge about the genesis of cancer, associated with an increased understanding about the mechanisms of response/repair and their influence on the mechanisms of mutation in the genes/chromosomes can influence the reliability of the LNT model, but with current knowledge it is still the most reliable model in terms of public

health [6].

Currently, induced genomic instability and bystander effect are among the mechanisms that cause post-irradiation adaptive responses in cells and that may also contribute to refute the LNT model. Even with such evidences supporting or refuting the LNT model, the ICRP remains the safest model to be used in issues of radiation protection, public health and safety [4-6].

3.2. Principles of Justification and Optimization of Protection

Acceptable risk (principle of dose limitation) is used with prior evaluation of another principle (justification) and a posterior one (principle of optimization). The two latter are source-related and apply in all exposure situations. These three principles are the basis of the protection system proposed by the ICRP and used since the recommendation 26 published in 1977 [7]. Their use is maintained in recommendation 60 from 1991 [5], and reinforced by recommendation 103 of 2007 [4]. The latter publication defines these principles as:

- (1) *Justification*: any decision that alters the radiation exposure situation should do more good than harm.
- (2) *Optimization of Radioprotection*: the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable (ALARA principles), considering economic and social factors.

The application of these principles allows the creation of regulatory targets that can be checked by ensuring that the use of radiation can be done safely. The security concept of justification is based on reducing the use, or rather to use radiation only when necessary. This posture helps to reduce the number of people exposed, exposure routes and sources that may cause exposure.

Secondly, the principle of optimization allows, once justified the use of radiation, that there will be a commitment through processes, rational use, planning, use of minor sources, more efficient equipment, control of exposure time, use of shielding, and that doses are as small as possible. Using

these principles in line can reduce the number of people exposed, the individual dose and finally the collective doses received by people, reducing the risk of operation with exposure to radiation because, according to the LNT model, any exposure generates a risk that is directly proportional to doses. Hence, the shorter the exposure the lower the dose and the lower the risk.

These two concepts are of easy application, although they can provide difficulties to precisely define the limits of application of radiological protection regulations. Differences in regulatory targets may become ambiguous and may result in inconsistent regulatory approaches inhibiting a coherent control of radiation exposure. Thus, the lack of coherence and consistency in regulations irregularities may occur and may affect the efficiency of radiological protection resulting in the establishment of unjustifiable barriers to international trade [4].

3.3. Exclusion, Exemption and Clearance

The concepts of exclusion and exemption fit two different situations. *Exclusion* refers to the deliberate omission of a situation of regulatory targets due to the impossibility of intervention to reduce risk, e.g. the concentration of K-40 in the human body. *Exemption* refers to waive from regulatory control because of the associated risks being contemptible, e.g. X-ray tubes of low intensity (maximum radiation emitted less than 5 keV), and *Clearance* being a special case of Exemption. They all were defined in ICRP Publication No 104 [8] as:

- (1) *the exclusion* of certain exposure situations from radiological protection control legislation, usually on the basis that they are unamenable to control with regulatory instruments (control cannot be regulated); and
- (2) *the exemption* from some or all radiological protection regulatory requirements for situations where such controls are regarded as unwarranted, often on the basis that the effort to control is judged to be excessive compared with the associated risk (control need not be regulated).
- (3) *the clearance* refers to relinquishing regulatory control of materials already regulated when such control becomes unwarranted.

3.4. Exposure Situations

Until the publication No 103 of ICRP [4], exposure situations were classified as practices (increased exposure) and intervention (reduced exposure). From this publication, exposure situations had their ratings changed to planned, emergency and existing exposure situations, and in each one can be held practices and interventions.

The exposure situations were defined in [4] and are

reproduced here as such:

- (1) *Planned* exposure situations are situations involving the deliberate introduction and operation of sources. Planned exposure situations may give rise to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures).
- (2) *Emergency* exposure situations are situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation, and require urgent action in order to avoid or reduce undesirable consequences.
- (3) *Existing* exposure situations are exposure situations that already exist when a decision on control has to be taken, including prolonged exposure situations that may remain in the aftermath of emergency exposure situations.

These exposure situations allow encompass all possible exposure situations, different from the previous classification. This classification allows including a larger number of situations in regulatory context.

3.5. Classification of Exposures

The ICRP recognizes three types of exposure: “occupational exposure, exposure of the public and medical exposure of patients” [4]. The exposure of comforters, careers and volunteers in research are treated separately. Occupational exposures are defined as exposures that occur in workers as a consequence of their work. The medical exposures are those occurring in patients due to diagnosis, intervention, and treatment of diseases with the use of ionizing radiation. Finally, the exposures of the public are those that are neither occupational nor medical exposures.

3.6. Levels of Radiological Protection

Recommendation No 103 of the ICRP [4] recognizes that, when individual doses are below the threshold of deterministic effect of radiation, the contribution of each source is independent of the contribution from other sources. One must also consider a source generating dose to more than one individual. This type of vision is called “source-related approach”. Sometimes, in situations of planned exposure, it is necessary to separate the occupational doses and the doses received by the public. In such cases, there are different restrictions of dose limits to the individual (be it worker or individual of the public). This type of vision is called “individual-related approach”.

These two approaches result in two visions of protection: that is, the protection of all individual sources or the effect of all sources on an individual, as described in Figure 1.

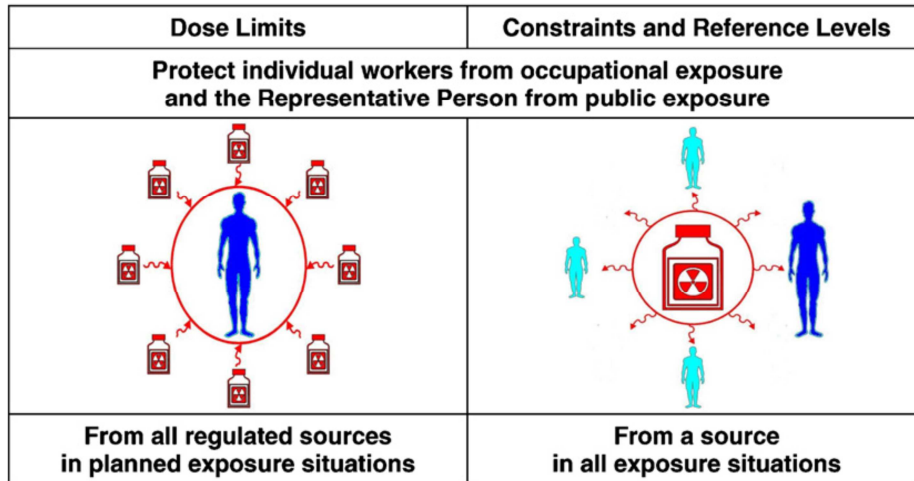


Figure 1. Dose limits contrasted with dose constraints and reference levels for protecting works and members of the public, following [4].

The relationship between dose limit, dose constrain, reference levels and exposure patterns recognized by ICRP [4] can be viewed in Table 3.

Planned expositions generally are within the regulatory control. The concepts of exclusion, exception and clearance

are used to justify when not using the regulatory control or to optimize the radiation protection regulations, when the risks are small enough for the removal of control or when the control is impossible to accomplish.

Table 3. The dose constrains, references level and types of exposure, following [4].

Type of situation	Occupational exposure	Public exposure	Medical exposure
Planned exposure	Dose limit Dose constraint	Dose limit Dose constraint	Diagnostic Reference level ^d (dose constraint ^c)
Emergency exposure	Reference level ^a	Reference level	N. A. ^b
Existing exposure	N. A. ^c	Reference level	N. A. ^b

^a long-term recovery operations should be treated as part of planned occupational exposure; ^b not applicable; ^c Exposure resulting from long-term remediation operations or from protracted employment in affected areas should be treated as part of planned occupational exposure, even though the source of radiation is 'existing'; ^d patients; ^e comforters, careers and volunteers in research only.

The generally existing exposure situations are outside the scope of regulation. Some cases of existing exposure can be framed in the regulatory targets, when the risk exposure is associated with a magnitude that justifies the application of radiation protection regulations.

For emergencies the concepts of exclusion, exception and clearance cannot generally be applied, except in cases where, after intervention, the exposure is framed as an existing exposure and might have to be put into the regulatory targets. In this case the concepts mentioned above can be applied to optimize the remaining exposure.

The ICRP [8] recommends the use of the concepts of exception, exclusion, and clearance, within the scope of national norms, where exposure can be considered unruly or not justified, as in the following cases:

- (1) cosmic radiation at ground level;
- (2) natural radioactive constituents of the human body; and
- (3) other cases.

The ICRP [8] has considered a number of specific situations where the definition of the scope may be particularly difficult and makes the following recommendations.

The following sources of low-energy or low-intensity external exposure of adventitious nature may be considered as candidates for exemption:

- (1) apparatus and devices that meet the following criteria in normal operating conditions:

- a) dose equivalent rate less than 1 $\mu\text{Sv}\cdot\text{h}^{-1}$ at a distance of 0.1 m;
 - b) the maximum energy of the emitted radiation is less than 5 KeV; and
 - c) sealed sources when dose rate is at least 1 $\mu\text{Sv}\cdot\text{h}^{-1}$ at a distance of 0.1 m.
- (2) other cases.

About activity concentration for radon in workplaces, the Commission continues to support the use of the single radon concentration value of 1,000 $\text{Bq}\cdot\text{m}^{-3}$.

Radiological protection regulations need not be applied to commodities in international trade that contain small quantities of radionuclides provided that they meet the applicable radiological criteria set out in relevant intergovernmental agreements.

4. Evolution of Radiation Protection After ICRP No 103

Since then, radioprotection continues to evolve based on the concepts described in ICRP publication No 103 [4]. Concerning the regulatory issue, publication No 104 [8] defined the regulatory scopes of radioprotection controls using the principles of justification and optimization and the exclusion, exception and clearance criteria of this scope.

Concerning technical aspects, publication No 107 redefined nuclear decay data aiming to improve the dosimetric calculations of radionuclides [11] and the internal dose assessment are revised in ICRP-133 [12]. In 2008, the applicability of the concepts of radioprotection in emergency cases was defined in document No 109 [1]. The year later, ICRP publication No 111 [13] supplemented recommendation No 109 [1], with procedures for radioprotection in the post-emergency period, classifying these situations as existing exposure and defined the safety procedures in this case.

Regarding the environment, it was only in 2008 that the scope of protection of biota was clearly defined in publication No 108 [14], using the concept of animal and plant reference, applying the same concept of man reference, used in ICRP No 103 [4]. Protection of biota evolved with publication No 114 in 2011 [15], with the definition of environmental parameters for dose calculation in biota, and in ICRP No 124 [16] with the formulation of environmental protection on different exposure situations.

In terms of occupational radioprotection, the ICRP recommendation No 110 redefined the man's phantom of reference for calculations of dose [17]; ICRP No 115 [18] assessed the radiological risk of cancer due to exposure to radon, and ICRP No 116 [19] redefined the conversion factors for external radiation. The ICRP No 126 [20] deals with protection against radon an environmental and occupational concern. Finally, Radiological Protection from Cosmic Radiation in Aviation is the focus of ICRP No 132 [21].

Concerning medical aspects, an overview was defined in ICRP No 105 [22]. Radioprotection of patients from radiopharmaceuticals procedures was analyzed in ICRP No 106 [23]. The radioprotection of overexposure in beam radiation therapy is addressed in ICRP No 112 [24]. Training and education in medical diagnosis and treatment is treated in ICRP No 113 [25], fluoroscopy in ICRP No 117 [226], cardiology in ICRP No 120 [27], pediatrics in ICRP No 121 [28], beam radiotherapy in ICRP No 127 [29], and tomography in ICRP No 129 [30].

5. Radiation Protection in Brazil

The recommendations of radiation protection in Brazil, mainly CNEN-NN-3.01 [2], because they are based on ICRP 60 recommendation [5] did not reach the state of the art of world radiation protection that is defined in Publication 103 [4] and which scope of application of control measures is defined in Publication 104 [8]. The changes from publication 60 [5] to 103 [4] and 104 [8] are significant, but the main considerations were not changed. The principles of justification, optimization and dose limit are maintained. The values of dose limits, though the model calculations have changed, as well as the radiation tissue weighting factors and significant discrepancies occur in the allowed values for intake of radionuclides that produce the same doses in the models proposed by ICRP 60 [5] and 103 [4].

Current recommendations of ICRP 103 [4] include a wider

range of exposures, maintain the possibility of inclusion and removal of regulatory targets of exposures that cannot be controlled or are not justified, especially at low risk.

Even not reaching the state of the art, standards in Brazil maintain a globally accepted standard of safety. The new recommendations of ICRP [4 and 8] were assessed by IAEA and with the release of the new guide [10], the old one [9] was replaced and the community is evaluating the new guide to adapt national regulatory norms and radioprotection as security given by this new guide [10] as its applicability. With time adaptations of national assessments will happen, but it is still too early for these changes to occur.

Although Brazil did not reach the state of the art described here, Brazilian law defines a scope for trusted security norms that allow working at safe radiation exposures, and being the legal norms for Brazil they must be obeyed.

6. Conclusions

Radioprotection is constantly evolving. New knowledge brings new philosophical and new technical approaches, based on the fundamental concepts of justification, optimization, and dose limitation. There is a time gap between the release of new recommendations, that formulate new approaches, and their eventual incorporation into country legislation, since these international recommendations have no legal value. To incorporate them into the regulatory scope of countries needs the creation and approval of new laws. From the 1990 ICRP recommendation No 60, the changes in radiation protection of occupational exposed people or patients were, as a rule, mainly on one-off issues and approaches. The major breakthroughs occurred on environmental aspects and non-human biota. As a matter of fact, all legislation based on ICRP No 60 and subsequent recommendations are able to protect quite adequately the environment and workers, although they are not in the state of the art as defined by the ICRP No 103 and subsequent recommendations.

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