Ethical, Legal, Social, and Epistemological Considerations of Radiation Exposure

12

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Learning Objectives

- To recognize that radiological protection is a matter of science and values.
- To appreciate that the acceptability of radiation risks needs to take into account more than the radiation dose alone.
- To identify risk perception and risk perception characteristics.
- To understand justification, being the first pillar of the system of radiological protection, as a principle instructed by the ethical values of justice, dignity, and autonomy.
- To understand the relevant underlying principles of nuclear law.
- To be aware of the general frameworks relating to nuclear law.
- To understand the difference between nuclear liability and general tortious liability.
- To realize that radiation risk communication should be theory-based, evidence-driven, and strategic.
- To get insight into how to communicate with general public and mass media about radiobiology.
- To get insight into the functioning of science and its impact on policy taking into account uncertainties and value pluralisms.

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12.1 Introduction

Ionizing radiation and radioactive substances can be natural or human-made. Humans have always been exposed to natural ionizing radiation (background radiation), because of the exposure of the Earth's surface to cosmic rays and the radioactivity contained in rocks that form the continental crust. The use of radiation and radioactive substances in medicine, research, industry, agriculture, and teaching, as well as the generation of nuclear power, have brought important benefits to society. Acceptance by society of the risks associated with radiation depends on the perceived relationship between these risks and the benefits to be gained from the use of radioactive sources. Logically, risks must be limited, and adequate protection provided. This does not mean that individuals or the environment must be protected from any and

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all effects of ionizing radiation, but rather to ensure that the amount of radiation absorbed does not have negative consequences that outweigh the benefits. The need to balance risks and benefits makes radiation a matter of science and values, meaning that in addition to technical assessments, ethical and legal issues also apply in the judgement of the acceptability of radiation risks.

12.2 The Radiological Protection System

After the initial and isolated observations of the first health effects of ionizing radiation (i.e., skin burns and cancers) by the pioneers at the turn of the nineteenth and twentieth centuries, two decades passed before a clear need for radiation protection was identified. One of the first signs was the leukemia epidemic that developed among radiologists after World War I, reflecting the use of X-ray radioscopy by military surgeons, without any kind of protection, to localize shrapnel in wounded soldiers. This epidemic lasted until the 1950s and affected approximately 500 radiologists [1].

To face the situation, the International Society of Radiology created the International Committee on Radiation Units (ICRU) in 1925 to develop the first concepts regarding dose quantification which were obviously needed. This was followed by the creation in 1928 of the International X-ray and Radium Protection Committee which was restructured in 1950 to take account of new uses of radiation outside the medical area and then renamed the International Commission on Radiological Protection (ICRP). Both ICRU and ICRP are still major actors of radiological protection.

Although the radiological protection (RP) system was established by ICRP, it is worth noticing the critical contribution of the United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR) created in 1955. The ICRP RP system is developed on the basis of the scientific knowledge gathered and synthetised by UNSCEAR.

The ICRP publishes a wide range of recommendations dealing with various aspects of radiological protection, but the current RP system with the three principles of justification, optimization, and dose limitation was first established with recommendation 26 [2]. It has been updated since then by recommendations ICRP 60 [3] and ICRP 103 [4].

12.2.1 Dosimetric Factors and Effects of Ionizing Radiation

ICRP has designed dosimetric factors to properly quantify the exposures to IR and then to establish links between dose and effects. The absorbed dose D is the energy deposited in the tissue: the unit of 1 J/kg is the Gray (Gy) in memory of James Gray. To take into account that different types of radiation do not produce the same biological effects for the same absorbed dose, a radiation weighting factor W_R is used to convert the absorbed dose into the so-called equivalent dose $H_R = W_R \cdot D$. This unit is the Sievert (Sv) in memory of Rolf Sievert. But the biological response also depends on the tissue and a tissue weighting factor W_T is used to convert the equivalent dose for each organ to the so-called effective dose E by adding the contributions of all organs $E = \Sigma_{R,T} W_T H_{R,T}$. The effective dose unit is still the Sv and when a dose is given in Sv it is mandatory to indicate if it relates to an equivalent dose or to an effective dose. Thus, only the absorbed dose is a physical parameter. Equivalent and effective doses are calculated parameters reflecting the likelihood of detriments in humans.

The effects of IR have been classified for years into two categories named deterministic and stochastic effects. Deterministic effects, e.g., skin burns, are due to high doses of ionizing radiation and the responsibility of radiation in their occurrence is clear. Deterministic effects always occur after a dose threshold is exceeded even though some individual variation exists, and the severity of the effect increases with dose. Stochastic effects, such as cancers, may occur after exposure to ionizing radiation but it is only possible to statistically express the occurrence. In other words, it is impossible to say who will develop cancer and when it will appear. One can only say that a percentage of cancers will appear in a population of persons exposed to a given dose, and the probability of developing cancer will increase with dose. Partly because of relatively high background rates of cancers in human populations, the establishment of a causal relationship between exposure to ionizing radiation exposure and the occurrence of cancer can be quite difficult (see Chap. 4).

More recently the separation between deterministic and stochastic effects does not appear to be so clear since some effects may combine both approaches, such as radio-induced cataracts. Therefore, ICRP now uses the classification tissue effect instead of deterministic effects.

Risk evaluation has resulted from epidemiologic studies that have established solid correlations (but not causality) between the frequency of cancers and the dose of IR in the dose range above 100 mGy. But ICRP recommendations are not so clear since the same numerical value is given sometimes in Sv. The calculated risk of cancer is roughly 5% per Sv of effective dose, while the risk to the developing fetus is 50% per Sv. The risk of hereditary disease has been estimated as 0.5% per Sv based on animal models, although it has not been documented so far in humans.

12.2.2 Practical Implementation of ICRP Recommendations

Epidemiologic studies have paved the way for effective management of radiation protection with the three ICRP principles of radiological protection, i.e., justification of all exposures, optimization of the justified exposures (ALARA principle), and limitation of doses for the workers and the population. Dose limitation does not apply for patients because doses need to be adapted for both diagnosis and treatment. The overarching goal was to suppress the deterministic effects and to substantially minimize the probability of the occurrence of stochastic effects.

On the basis of scientific evidence, ICRP has progressively recommended the mandatory decrease in the exposure to the level of low doses. The actual exposure of workers to ionizing radiation has clearly decreased over the years and is now in the order of or below 1 mSv/year of effective dose in most countries, although the legal limit is still 20 mSv/year for the effective dose. The dose limit of 1 mSv effective dose for the public is below the variations of natural background. At present, the dose limits of the system of radiological protection are quite low and are therefore not foreseen to be changed in the near future. However, doses from medical exposures are still steadily rising.

The ethical foundations of the system of radiological protection were reviewed by ICRP in its publication 138 [5]. This underlined that radiological protection is not only a matter of science but has been developed on ethical values either intentionally or indirectly. Four core ethical values (beneficence/non-maleficence, prudence, justice, and dignity) underpin the present system and relate to the three principles of radiological protection. This publication also addresses key procedural values (accountability, transparency, and inclusiveness) required for the practical implementation of the system (see the following section for more details).

Although the system of radiological protection developed and updated by ICRP for more than eight decades has proved robust and operational, there remain a number of ethical, legal, and social challenges

- Risk evaluation is a major concern since this drives the allocation of resources for radiation protection. The majority of doses in humans are in the low-dose range with a very low risk of cancer. The effective dose should not be used for risk evaluation for a specific individual [4]. Regarding medical exposures, there is a need to develop individual risk evaluation based on doses to the organs exposed [6].
- The human individual response to ionizing radiation should be included in the system in order to optimize radiological protection. This will be part of personalized and predictive medicine, for example, in persons with a high familial risk of cancer or in patients who are likely to be repeatedly exposed to ionizing radiation for medical reasons (especially children, women, prior to radiotherapy or to repeated screening).
- There should be an increased focus on communication with the public and media. There is a need to understand the psychological aspects of risk perception, especially when these show diversion from the real exposures and risks.

12.2.3 The Ethical Motivation for the Linear Non-Threshold Hypothesis

Discussion about the meaning and appropriateness of the acronym LNT has been central in the debate on radiation protection against low-level exposure situations. As an acronym, LNT is non-translatable; a fact that does not facilitate communication. LNT is aimed to denote an imprecise expression: "linear-non-threshold," a short reference to the relationship between the probability of suffering a radiation health effect and the incurred radiation dose, following low doses, low dose rate, radiation exposures.

It is to be noted that this imprecise acronym has been widely used with different connotations by relevant professional communities, a conundrum that can be simplistically summarized as follows:

- For radiation biologists, LNT usually refers to a biological hypothesis postulating that at low radiation doses a given increment in dose will produce a directly proportionate increment in the probability of incurring malignancies or heritable effects attributable to radiation.
- For radiation epidemiologists, LNT is an epidemiological conjecture by which the incidence of effects per unit dose measured at radiation exposure situations involving relatively high doses delivered at relatively high dose rates, where an epidemic of increases in malignancies have been recorded, is presumed to occur also at radiation exposure situations involving low doses and low dose rates in spite that epidemiological evidence is not achievable in such situations.
- For radiation-protectionists, LNT represents a practical operational model for managing radiation protection and controlling that protection against additional doses regardless of the level of accumulated dose, and, therefore, preventing discrimination—particularly age-related labor discrimination in cases of occupational radiation protection.

The wide and imprecise use of the acronym LNT without clarification of its precise meaning has been a cause of serious confusion on the health effects attributable following low dose, low dose rate, and radiation exposure situations.

It could be succintly said that LNT is intended to mean a practical model rather than a sophisticated scientific theory and that it is based on the globally accepted principles of ethical prudence and on labor rights for non-discrimination—long established by international undertakings.

12.3 Ethical Aspects of Radiation Exposure

12.3.1 Radioactivity and Justification: Raising Awareness for the Contexts of Concern

What are we speaking about when we speak about ethical, legal, social, and psychological aspects in relation to the radiological risk? Dealing with radioactivity in society is a complex challenge in any respect, but one can distinguish four fundamental "contexts of concern" that require different visions on complexity, and what it would mean to responsibly deal with it. When considering ethical, legal, social, and psychological aspects of radiation exposure, it is important to always do this with the context of application or "the context of concern," in mind.

The first context is the context of "naturally enhanced" natural radiation. The second context concerns industrial practices that involve technically enhanced natural radiation. The third context is the context of peaceful applications of nuclear technology. These include applications of nuclear physics processes, such as the fission or fusion of nuclei for energy production or the use of decay radiation in medical treatment and diagnosis or for industrial purposes. The fourth context is the use of nuclear technology or material as a weapon, either as a means for political deterrence, in organized military operation or in terrorist actions.

The reason to distinguish these different contexts is motivated by a specific understanding of the ethics of radiological risk governance and its relation to the social and political aspects of governance, and this as well in theory as in practice. To put it simply, if we consider average natural background radiation as an element of our natural habitat, then any significantly enhanced level of radioactivity in the vicinity of living species represents a risk—in the sense of a potential harm—to the health of those living species. In these cases, pragmatic reasoning thus requires us to consider the possibility of protection, mitigation, or avoidance, but essentially to first evaluate why the additional radioactivity occurs in the first place, and whether we can possibly justify it. But whether that justification exercise can be done meaningfully or not depends on how we perceive the context of the occurrence of radiation.

From what the first context is concerned, whether we want it or not, natural radiation is there and any naturally enhanced occurrence (e.g., in the case of high concentrations of Radon) has a potential impact on health. Thinking in terms of justification of the presence of that radiation is meaningless, which leaves us with evaluating the justification of exposure, and thus of the possibility of protection, mitigation, or avoidance of its impact.

In the second context of technically enhanced natural radiation (for example, in the oil refinery industry or in aviation), radiation exposure manifests as a "side effect." Practices as such may be contested (as is the case with the oil or phosphate industry), but very rarely the issue of radiation exposure will become a decisive factor in the evaluation of the justification of these practices. Similar to the case of naturally enhanced natural radiation, the radiation justification exercise thus restricts itself to the evaluation of exposure, and thus to the evaluation of the possibility of protection, mitigation, or avoidance of its impact.

In the third context, evaluation of the justification of the use of nuclear technology obviously takes the reason for that proposed use (the projected "benefits") as a first criterion, with the aim to "balance" it with the projected risks. Despite the fact that opinions on these projected benefits and risks differ among people, in this context, an evaluation of the justification of the use of a risk-inherent technology, or thus of the presence or "creation" of radiation, remains meaningful, and this is because the application context is "neutral"; while opinions may differ on how to produce energy or perform a medical treatment, nobody is "against energy" or "against medical care" as such. The neutral context thus makes a meaningful joint evaluation of the justification of the nuclear technology application possible, and it will not affect possible outcomes (rejection or acceptance of the technology) as such.

Finally, in the fourth context, a meaningful joint evaluation of the justification of (the risk of) the nuclear technology application is not possible, and this is for the reason that the context of application itself is not neutral. A pacifist perspective does not support a principal justification of nuclear deterrence and armed conflict strategies, while, in a perspective that sees politics always as a politics of power and conflict, these strategies may be perceived as justified.

12.3.2 The Justice of Justification as a Central Ethical Concern

Any evaluation of the acceptability of a radiological risk is characterized by a "double" complexity. Firstly, it needs to take into account the uncertainties with regard to whether and how the risk will manifest. Science has an authoritative voice in this evaluation, but it needs to recognize that there will always be uncertainties that cannot be cleared out (stochasticity of biological effects at low radiation dose, possible delayed harm of medical diagnosis or therapy, the possibility of a nuclear accident, the fate of a radioactive waste disposal site in the far future, …). In addition, we have to accept that important factors remain to a large degree beyond control: human behavior, nature, time, and potential misuse of technology… Secondly, an evaluation of the acceptability of a radiological risk also needs to consider diverse value judgments with regard to the acceptability of the risk. In philosophical terms, one can say that the evaluation is troubled by moral pluralism: even if we would all agree on the scientific knowledge base for the assessment of the risk, then opinions on its acceptability could still differ. The reason is that evaluations of acceptability do not only rely on "knowledge" but are also influenced by references to things people value as important, such as freedom, security, the value of nature, the rights of the next generations, and their safety and that of their loved ones. In that case, science may thus inform the technical and societal aspects of options, it cannot instruct or clarify the choice to make.

Taking this complexity into account, one may understand that risk cannot be justified through a one-directional "convincing explanation" by scientific experts or political decision-makers. Ethics supports the idea that the evaluation of a possible justification of a radiological risk needs to be done in deliberation among all concerned, including those potentially affected by the risk. In that deliberation, visions from science, policy, civil society, and citizens have an equal place, bearing in mind that (quoting the philosopher Philip Kitcher) "*There are no ethical experts. The only authority is the authority of conversation*" [7]. Obviously, the outcome of that conversation can either be to reject or to accept the radiological risk. In other words, from an ethical perspective, the argument is that the justice of justification, ensured by the possibility of self-determination of the potentially affected, should be the central concern of risk governance. In practice, that means formal methods for decision-making and formal procedures within the organization should care for the possibility of participation of those potentially affected by the radiological risk.

12.3.3 Recognizing the Limits of the Radiological Protection System for Risk Justification

Seen from a different perspective, ethics in relation to radiological protection is also about considering and recognizing the limits of the radiological protection system when it comes to providing a rationale for justification of radiation risk. In other words, we cannot question the ethical dimensions of the radiological protection system without also questioning the ethical dimensions of the "bigger" systems in which the radiological protection system operates and on which it depends. Given that the radiological protection system, in its concern for providing guidance for decision-making, relies on science but also and essentially wants to take into account human and societal values, the bigger systems that need to be questioned in terms of their ethics, are those of knowledge production (research and policy advice) and decision-making. For risks that manifest in medical diagnostic or therapeutic practices, that "system" is the possibility of deliberative dialog between the patient, the doctor, the nurse, the radiation control and protection service of the hospital, other hospital agencies, as well as regulatory and professional bodies. For risks that manifest in an occupational context, the system of decision-making is the radiation control and protection service, the management system of the organization, other relevant agencies, trade unions, and professional bodies. For risks that manifest on a societal level, that system of decision-making is the system of democracy, including input from citizens, civil society, trade unions, professional bodies, advocacy groups, and of scientific and ethical advisory committees.

12.3.4 The Ethical Foundations of the System of Radiological Protection

The evolving ethics of the developing international system of protection against ionizing radiation could be viewed as the branch of some kind of embryonic radiological protection philosophy, which from the beginning of the profession was dealing with main protection principles and their values. It challenged questions about the morality of the protection principles—that is, concepts such as good and bad, right and wrong, virtue and vice in radiological protection. It tried to tackle issues such as the meaning and reference of moral propositions on radiological protection; the practical means of determining a moral protective action, how moral protective outcomes can be achieved in specific situations, how a moral capacity for recommending a protection paradigm develops and what its nature should be and what moral values on radiological protection people in general and stakeholders in particular should actually abide by.

Ethics was the primordial earliest concept for judging human actions such as those involved in radiological protection and provides its fundamental basis. Radioprotectionists had been (and continue to be) very keen on exploring and reassessing the rules and standards governing their professional conduct. They have had an unusual curiosity to self-inspect whether they hold the right behavior and what is the set of principles for self-ensuring that such behavior is right. This interest in self-appraisal of conduct correlates with the notion of ethics.

The ethical basis of radiological protection was early recognized by the profession's forefathers [1]. The primordial radiation protection principle related to individuals (in fact these individuals were at the beginning just radiologists; it would take a number of years to incorporate individual members of the public, and some more to incorporate individual patients undergoing radiodiagnostic or radiotherapy), as follows:

- The *principle of individual dose restrictions*, which was aimed at ensuring that the total dose incurred by any individual should be restricted to protect the individual exposed. Although not explicitly, it was implicitly based on an ethics of duty, the so-called *deontological ethics*, which is usually expressed with the aphorism "One should do unto others as they would have done unto them."

Over time it became clear that the protection of individual was a necessary but not necessarily a sufficient condition, and the system of collective ethical requirements evolved. Two basic principles would fill this gap, as follows:

- The *principle of justification*, which was aimed at ensuring that any decision that alters the radiation exposure situation should do more good than harm—meaning that by introducing new radiation sources or by intervening for reducing existing doses, sufficient individual or societal benefit should be achieved to offset the detriment such actions may cause. This principle was based on the ethics of consequence or *teleological ethics*, which is usually expressed with the aphorism "The ends justify the means."
- The *principle of optimization*, which aimed at ensuring that the level of protection would be the best under the prevailing circumstances, maximizing the margin of benefit over harm, and thus the number of people exposed and of their individual doses be kept as low as reasonably achievable, taking into account economic and societal factors. This was based on the ethics of efficacy or *utilitarian ethics*, which is usually expressed with the aphorism "Provide the greatest good for the greatest number of people."

These two principles and their ethics are the basis of the radiation protection paradigm recommended by the ICRP.

In addition, there was an intrinsic value of these principles, or de facto principle in its own right, which unfortunately was not specifically declared as such by ICRP, but which is implicitly referred to in many statements and underlines most of the ICRP recommendations and it was recognized in subsequent international standards. It could be formulated as follows:

- The *principle of intergenerational prudence,* also termed *principle of protection of present and future generations* in international standards, is aimed at ensuring that protection extends to all humanity and its environment, regardless of where and when people live, and which implies that all humans, present and future, and their environment shall be afforded with a level of protection that is not weaker than the level provided to those populations causing the protection needs. It can be construed that this important principle is mainly based on the *ethics of virtue* or *ethics of arête*, which is usually expressed with the aphorism "No return should be expected from good actions, as goodness is an ideal that transcends human nature.".

Teleological and utilitarian ethics belong to a family of "social-oriented" ethics; deontological and arête ethics belong to a family of "individual-oriented" ethics. In relation to radiation protection, teleological and utilitarian ethics aim at protecting society as a whole, while deontological and virtue ethics are more focused on individual protection and individual rights. Teleological, utilitarian, and deontological ethics have evolved in a mainly anthropocentric framework. Conversely, arête ethics is able to deal with more general ethical issues such as intergenerational and environmental protection.

The start of the twenty-first century saw a growing criticism of the anthropocentric focus of the system of radiological protection, exemplified by the statement that "… *the standard of environmental control needed to protect man to the degree though desirable will ensure that other species are not put at risk*" [3]. Critics noted that there were cases where human doses could be low and doses to wildlife high (e.g., waste disposal), that the approach was not in line with management of other environmental stressors, and that there was a need to demonstrate explicitly that non-human species were being protected [8–10]. The IAEA published a report on "*Ethical Considerations in protection of the environment from the effects of ionising radiation,*" exploring ethical principles that might underlie a system of protection and stressing the need to be compatible with international legal instruments such as those related to sustainability and protection of biodiversity [11]. The requirement to address the impacts of ionizing radiation on the environment is now included in international radiation protection recommendations and standards [4, 12, 13].

12.3.5 ICRP Core Ethical Values

Previous writers have compared the ICRP principles with ethical theories, highlighting the similarities between the principle of justification with teleological or contractarian ethics, the principle of optimization with utilitarian approaches, and the principle of dose limitation with deontological ethics [14, 15]. In its recent work on the ethical foundations of radiological protection, ICRP has focused on commonly recognized ethical values, rather than overarching ethical theories such as utilitarianism or deontology [5]. This is in line with approaches to ethical assessment applied in biomedical and public health ethics [16], as well as work on cross-cultural ethics [17], underlining that it is easier to find agreement on fundamental values than on ethical doctrines. ICRP highlights four core values underpinning the system of radiological protection: beneficence/non-maleficence, justice, dignity, and prudence [5].

Examples of how these values can be applied in the analysis of ethical challenges are given in the following sections. But briefly, beneficence and non-maleficence refer to the principles of promoting well-being and avoiding the causation of harm. In radiological protection, this is clearly related to the reduction of radiation exposures, and the avoidance of resultant harms, but can also include a range of different costs and benefits, including economic and societal aspects. There will always be questions about how to measure consequences and who or what should count in such an evaluation (e.g., animals and future generations). Dignity is concerned with respect for autonomy and the self-determination and choice of affected populations and includes issues related to privacy, human rights, as well as individual and community empowerment. The ethical principles of fairness and justice stress the importance of addressing the way in which risks, costs, and benefits are distributed (distributive justice), as well as the way in which decisions are carried out (procedural justice). Prudence is the ability to make discerning and informed choices without the full knowledge of the scope and consequences of our actions. While precaution and prudence are rarely alluded to in general medical ethics and bioethics, the precautionary principle is well recognized in environmental ethics. The ICRP also introduces the procedural values of transparency and accountability, in the practical application of radiological protection, especially in the need to engage stakeholders in decision-making processes [5]. While there has been a general consensus on the fundamental values proposed by ICRP, there have been proposals that the system should include additional values such as empathy and honesty [18].

12.3.6 Acceptability of Radiation Risks Need to Address More Than the Size of the Dose

The public's aversion to radiation—and especially that associated with nuclear power rather than natural or medical exposures—is often cited as an example of irrationality or misunderstanding, and is best combated by improved education. But to understand risk perception, we need to recognize that risk is in part quantifiable but also a social construct that is interpreted differently by people in various situations, environments, and cultures. It is true that people misunderstand probabilities; however, numerous studies of the psychological and psychometric factors that influence risk perception show that the situation is more complex than this alone. Public or lay perceptions of risk vary widely between people and can differ from the calculated, technical approach to the assessment of risks. Whereas an expert will often tend to rank risks as being synonymous with the size or probability of harm, risk tolerance or aversion is dependent on many additional characteristics [19, 20]. Many of the characteristics have strong psychological as well as societal and ethical relevance (such as control, voluntariness, and distribution of risks and benefits).

12.3.6.1 Autonomy, Personal Control, and Consent

People tend to be less tolerant of risks that are imposed without their choice or personal control. The phenomenon applies to a range of different risks and actions, such as driving a car compared with flying. Personal control is closely related to the fundamental ethical value of autonomy (i.e., respect for the free will of individuals), dignity, integrity, and individual rights. It is also linked to the requirement for free informed consent within medical ethics and can explain why people are less concerned over medical radiation exposures (which are largely voluntary and for an obvious personal benefit). People often feel a lack of personal control over radiation exposure [19], particularly those associated with accidents. They are dependent on information from authorities or media and have to deal with both the risks from the exposure as well as the consequences of measures to reduce exposure such as relocation or agricultural bans.

In risk management, measures that increase personal control and understanding, such as the provision of dosimeters or counting equipment, and participation in decision-making are considered positive and can help populations in coping. Provision of counting equipment and independent monitoring are methods that have been successfully applied in both Chernobyl- and Fukushima-affected communities [21–23]. When combined with access to experts to help interpret results, such actions can help empower populations. Ethically, procedures that involve the populations themselves can help promote the principle of informed personal control over radiation risks.

12.3.6.2 Community Values and Societal Consequences

The Chernobyl and the Fukushima accidents both resulted in a wide range of social and economic consequences. Many evacuees lost their jobs, social network, and connection to places of a particular community or historical value like graveyards or places where they played as children [24]. Resettlement and long-term evacuation in Fukushima have changed the social structure of the villages and city districts [25]. After Chernobyl, the emigration of young people impeded the whole social and economic development of the region, including a shortage of teachers and doctors [26]. Similar demographic changes have been seen after Fukushima, with young families more likely to evacuate and less likely to return [25]. These lead in turn to a variety of social and health effects such as alcoholism, obesity, and depression in affected populations.

The economic costs of accidents are complex and wide-reaching. Loss of consumer trust in food from a contaminated area can have economic consequences that go beyond the loss of food production. Stress, ill-health, and even suicide can accompany job loss and bankruptcy. Loss of consumer trust can have profound consequences both for a range of industries (particularly food or tourist industries) and for the local identities of people and groups. This has been well-documented in Fukushima with price drops for produce from the entire region, including areas not affected by the accident, as well as impacts on tourism [25]. Negative economic side effects can arise from rural breakdown and stigma of contaminated communities. Discrimination and stigmatization of the Hiroshima and Nagasaki Hibakusha and their children have an important historical dimension in Japan [27] and is a particular concern for Fukushima evacuees. Hibakusha is a Japanese term referring to the survivors of the Hiroshima and Nagasaki atomic bombs, which translates literally as "bomb-affected people." TEPCO workers also cited discrimination as one of the main causes of psychological stress [28]. In addition to experienced prejudice, concerns of the populations affected by Fukushima Daiichi accident include worries about whether their children would be able to find partners or marry in the future and reports of discrimination against Fukushima children after moving to new schools.

The aftermath of an accident can also be economically beneficial to parts of the community, for example, through the generation of local employment opportunities. This may lead to some sections of the population making a profit from remediation (such as selling or hiring equipment), which can lead to further social inequity and division.

12.3.6.3 Distribution of Risks and Benefits

Distribution of the costs, risks, and benefits of radiation exposure relate to the fundamental ethical values of equity, justice, and fairness. After an accident, doses received by individuals can vary widely, and the risks of those exposures differ between adults and children. The consequences of remediation can impact different members of the affected communities. Some may lose their livelihood, while others can continue more or less as before the accident. For example, after Fukushima the situation was particularly harsh for the elderly evacuees, particularly those living in temporary housing who experienced greater isolation from family and communities [25].

The potential for increased health risks from radiation in children means that the risk perceptions go beyond consideration for personal risks, as is seen by anxiety over thyroid cancer in Fukushima populations [35, 36]. The fear that your child could be affected in the future can overshadow any personal concern [24]. Such concerns create challenges for health surveillance, particularly thyroid screening of children. While parents may, understandably, request screening, the procedure can lead to unnecessary surgery (e.g., 4000 thyroid surgeries in Chernobyl children may explain most of 15 deaths attributed to exposure), and without a carefully thought communication plan may raise anxiety (Shamisen 2020). Some measures to reduce exposures could result in an equitable distribution of cost and dose reduction, such as investment by taxpayers to reduce activity concentrations in public areas; while others are less equitable, for example, when a reduction of dose to the majority is only possible at the expense of a higher dose, cost, or welfare burden, on a minority (e.g., banning all farm production in a small community).

To conclude, public reaction to disasters is the result of complex and intrinsic features of risk perception, many of which have strong ethical and societal relevance. A holistic approach to disaster management should integrate economic, ecological, and health measures. Risk management strategies should be designed to accommodate varied needs. For nuclear accidents, it is not sufficient to simply focus on the dose reduction aspects of radiation protection as societal aspects will play a major role in how individuals cope with, and communities recover from the disaster. Engaging with the affected population with regard to increasing their understanding and personal control and involving them in decision-making processes respects people's fundamental right to shape their own future. In addition to increasing trust and compliance, such approaches can lead to significant improvements in the effectiveness and acceptability of disaster management in communities.

12.3.7 Emerging Occupational Challenges from New Methods to Determine Individual Radiosensitivity

Testing for radiosensitivity has the potential to improve patient treatment and diagnosis or protect workers. Assays might be applied prior to radiotherapy, to avoid adverse reactions in radiosensitive individuals, or to avoid enhanced cancer risk in connection with radiodiagnoses such as CT scans or mammography [31]. While not yet applied in medicine or worker protection, assays are currently under development, and their potential application raises a number of ethical and legal challenges. These go beyond the simple question of whether the assay will "do more good than harm" to include, for example, questions about how the costs and benefits might be distributed in society, concerns about privacy and data protection, and considerations of the potential for discrimination.

12.3.7.1 Well-Being

Radiosensitivity and radiosusceptibility assays have a clear potential to provide physical health benefits by improving cancer treatment, avoiding negative side effects, and enhancing worker protection. There are also economic aspects, such as balancing the cost of the assays against the opportunity to save money through tailored treatment. Psychosocial consequences could include reassurance but might also cause worry about sensitivity to other stressors. Information on the magnitude of the effect, its relation to other potential risk factors, and indeed any dose–response relationship, as well rates of false positives and false negatives would be needed to be able to balance the physical harms and benefits. But this would also have knock-on effects on economic, psychological as well as legal assessments. Could doctors be sued for the negative effects of not carrying out a test?

12.3.7.2 Dignity and Autonomy

Information on individual radiosensitivity and radiosusceptibility could clearly enhance patient or worker empowerment and personal control, but this would depend strongly on the context in which this information was used. The issues are similar to other challenges with personal health information, such as conforming to data protection laws and the increasing commercialization of genetic testing [32]. For example, the degree to which data from patients undergoing an assay as part of radiotherapy would be stored, anonymized, and made available for further research would need to be addressed. A debate on the implications of these issues would need to include engagement with the various stakeholders but could also play an important role in risk communication, by putting the risks of ionizing radiation in context with other environmental and genetic risk factors.

12.3.7.3 Justice and Fairness

Increased understanding of the differences in radiosensitivity within populations is relevant to an assessment of justice. Other questions would include whether the assays would provide equal access to health care and support or have any impact on health insurance (would sensitive populations have to pay higher premiums?) or compensation claims (will it change the balance of probabilities that cancers were caused by radiation exposure?). Even in countries with national health insurance, there is the question of whether people should be obliged to disclose the results of genetic testing before taking out private health or life insurance schemes. If sensitivity or susceptibility was linked to a genetic trait, there would be additional issues associated with implications for children or other family members. While identification of increased radiosusceptibility in workers could be used for protective purposes, it might also lead to discrimination, or raise questions about "responsibility" for any diseases or negative side effects (lifestyle, predisposition, occupational exposure, etc.). These issues could be linked to broader debates on the implications for radiological protection of populations with different risk factors such as whether children or women should be treated differently on the basis of increased radiation cancer risks.

To conclude, many of the ethical challenges associated with the field of radiosensitivity and radiosusceptibility have parallels with existing challenges in medical, occupational, and public health. They also raise important questions about the implications for radiological protection. For example, will population-level differences in radiation susceptibility impact the assessment of health risk? Will they lead to a change in dose constraints? These questions can only be addressed with the participation of a wide variety of stakeholders. Assessing the implications for well-being requires knowledge from experts in radiation biology, medicine, occupational health, health economics, social scientists, etc., as well as transparency about uncertainties and assumptions. Respecting both the principles of dignity and fairness in the procedure requires the participation of affected persons (workers, patients, the public, etc.) in decision-making.

12.3.8 The Ethical Challenge of Science as Policy Advice

Looking at the societal impacts of science and technology, nuclear technology probably represents the most extreme case of how science and technology can serve both cure and destruction. While medical applications of nuclear technology save individual lives every day, nuclear weapons have enormous destructive potential. Nuclear energy is a low-carbon source of electricity, but a nuclear accident can have dramatic impacts on the environment and on the physical and psychological health of a whole population for a long time. In addition, disposal of radioactive waste unavoidably requires taking responsible action toward future generations thereby taking into account time dimensions longer than ever faced before in human history.

The case of nuclear energy technology is also an example of how technology assessment can be troubled by the fact that "benefits and burdens" of a technology are essentially incomparable. Referring to the general considerations related to the radiological risk and the need to include values in its assessment above, we can say that, taking into account the specific character of the nuclear energy risk, also the societal justification of nuclear energy is troubled by moral pluralism. That is, even if we would all agree on the scientific knowledge base for the assessment of the risk, then opinions on its acceptability could still differ. The matter becomes even more complex if we take into account the fact that science can only deliver evidence to a certain extent. Nuclear science and engineering are mature, but we have to acknowledge that the existence of knowledge-related uncertainties puts fundamental limits to understanding and forecasting technological, biological, and social phenomena in the interest of risk assessment and governance. Last but not least, we have to accept that important factors remain to a large degree beyond control. These are human behavior, nature, time, and potential misuse of technology.

The resulting room for interpretation complicates the evaluation of risk-inherent technologies in general and of nuclear technology in particular and puts a specific responsibility on science and technology assessment as a policy-supportive research practice. And this is the point where ethics come in. In simple terms, that responsibility comes down to acknowledging and taking into account uncertainty and pluralism as described above, and the consequences thereof for research and policy. That "responsible attitude" does not only apply to scientists but to everyone concerned with applications of science and technology in general and with the issue of nuclear technology in particular. The idea is that this responsible attitude can only be enabled and stimulated in "interaction methods" for policy and scientific research that are able to generate societal trust by their "method." Today we know that this in principle translates as doing politics differently by involving the potentially affected and other stakeholders in deliberative decision-making, and as doing science differently, namely as transdisciplinary science advancing from a holistic perspective and enriched with insights and ideas from the social sciences and the humanities, from lay knowledge and the arts and from civil society and citizens (see, among other [33–35]). For science in particular, confronted with the need to deal with incomplete and speculative knowledge and value pluralism in providing policy advice on issues of social well-being, its challenge is no longer the production of credible proofs but the construction of credible hypotheses [33]. From an ethical perspective, in the general interest of rendering hypotheses with credibility (and the potential to generate societal trust), one could say science has no choice but to "open up its method" for transdisciplinarity and public involvement, in addition to the "traditional" quality criteria of objectivity and independence and the need to recognize uncertainty, value pluralism, contingency, and potential misuse. Obviously, the aim of this ethically inspired "reflexivity" is not to undermine the credibility of science but to stimulate dialog and (self) critical thinking, and to make science more resilient against pressure from politics and the market to deliver evidence it cannot (yet) deliver.

12.3.9 Emergency Planning and Response in Post-Accident Context

The complex dimensions of radiological risk, particularly after large-scale accidents raise particular challenges for cost-benefit analysis of post-accident response. Emotional descriptions of such emergencies seem more common than quantitative cost-effectiveness considerations. Noteworthy, a few weeks before the first atomic bomb test in July 1945, an official report warned that "civilization would have the means to commit suicide at will" [36]. Kahn [37] considered a full-scale 10,000,000 kiloton nuclear exchange between the Soviet Union and the USA, and deliberated in detail why the above statement is far from being based on evidence.

Quantitative considerations show that the direct health consequences—radiation sickness, carcinogenesis, etc.—of any past (or future practically probable) radiological accident are much less far-reaching than those which are usually perceived. In each scenario, direct health effects are only a small part of the damage caused by fear and anxiety. For example, the two major humanitarian disasters after the Chernobyl and Fukushima nuclear accidents turned out to be such disasters not because of their radiogenic effects, either actual or averted. The main health consequences could be attributed to countermeasures by the authorities, and socio-psychosomatic problems among the public. The relocation of hundreds of thousands of people created very real suffering, morbidity, and mortality [38]. Rational decision-making should have quantitatively compared the human cost of evacuation and long-term relocation with the human cost of radiation exposure. Such comparison was performed only decades later. For example, Yanovskiy et al. [39] estimated that in Fukushima the evacuation was not justified at all, and in Chernobyl the evacuated zone could have been repopulated after 1 month.

The human cost of evacuations should be considered as follows. First, there is always a direct loss of life due to the temporary loss of medical care, psychosomatic disorders, and even suicides; After Fukushima, e.g., 1% of the evacuees died during the first 2 years due to evacuation-related causes (on top of the natural mortality). Second, evacuees' quality of life deteriorates by about 20% [39]. Last but not least, evacuation is expensive. While associating human life with monetary value is psychologically difficult and may seem ethically challenging, it is actually an ethical necessity since extraneous expenditure leads to a statistical shortening of life. A cost-effectiveness analysis is routinely performed when formulating health policies [40]. Safety expenditures should be treated in a similar way since both healthcare and safety deal with life extension [41].

In this context, it is worth mentioning that life expectancy varies considerably not only for different countries but also for different locations of each country: the main reasons are probably socioeconomic and environmental. This disparity in life expectancy across countries is typically of several years; in the extreme case of Calton in the UK it was 25 years below the country average [42]. It is needless to mention that evacuation of less-successful locations is nowhere considered as a viable option.

12.4 Legal Aspects of Radiation Exposure Situations

12.4.1 Introduction

The purpose of nuclear law is to establish a legal framework for the safe management of all sources and types of radiation and endeavors involving exposure to ionizing radiation [43]. Nuclear law should thus ensure the adequate protection of individuals, society, and the environment, both present and future, against radiological hazards. Specifically, nuclear law should cover the exposure of the general public—i.e., any individual in the population—of workers—i.e., any person who works, whether full-time, part-time, or temporarily, for an employer and who has recognized rights and duties in relation to occupational radiation protection—as well as exposures related to medical uses of radiation, situations in which a patient is voluntarily exposed for therapeutic purposes (radiodiagnostic or radiotherapy) and who may incur high doses of radiation, possibly with unwanted side effects as a result. Radiation protection rules and regulations should always include special provisions relating to the way in which the application of fundamental principles of justification of actions involving radiation exposure, optimization, or protection, and limitation of individual radiation risk is applied.

The general principles of nuclear law broadly apply to all nuclear-related activities and facilities where ionizing radiation is used or produced.

Section 12.4 will first define nuclear law. Important principles will then be covered followed by a summary and explanation of relevant legislative frameworks. Certain specific potential exposure situations and how the law treats them will also be expanded upon such as employer and medical liability, as well as the legal framework for airline personnel and astronauts.

Legal attribution and imputation of radiation harm to radiation exposure situations, a topic that has distinct epistemological elements, will be discussed in Sect. 12.5 after the more formal legal aspects.

12.4.2 Definition and Objective of Nuclear Law

The scope of nuclear law can be succinctly defined as any issue or matter relating to the use of, production of, or exposure to ionizing radiation in specific situations.

In more detail, nuclear law can be defined as "*The body of special legal norms created to regulate the conduct of legal or natural persons engaged in activities related to fissionable materials, ionizing radiation, and exposure to natural sources of radiation*" while its primary objective is "*To provide a legal framework for conducting activities related to nuclear energy and ionizing radiation in a manner which adequately protects individuals, property, and the environment*" [44].

This definition has four key elements. Firstly, nuclear law is a body of special legal standards and norms. These are recognized as a part of general national legislation. Since it is a sovereign right of countries to choose how they enact laws, national legislations may differ when it relates to nuclear issues.

Secondly, nuclear law serves a regulatory purpose. The use of and exposure to radiation needs to be regulated given that whilst there is a potential benefit to social and economic development, there also a potentially detrimental effects.

Thirdly, nuclear law relates to the conduct of legal and natural persons. These persons could be commercial, academic, scientific, governmental, or natural. A legal person is a body corporate (or corporate organization) such as a company while a natural person is an individual human being [45].

Fourthly, nuclear law primarily relates to radioactivity, ionizing radiation, and the products of nuclear fission, with the clarification that in this context, it means those that have potentially unwanted biological effects. We could add to the definition that the effects of fusion reactions—still largely in a developmental phase at the time of the redaction of this work—should also be included under the umbrella of nuclear law. The property of protection of the population from the adverse effects of radioactivity and radiation is considered to be the defining aspect justifying the need for a special legal regime.

12.4.3 Principles of Nuclear Law

A number of basic concepts, often expressed as fundamental principles, distinguish nuclear law from other aspects of law. These principles and various theories are crucial to understand because they help understand why the law exists in the form it does.

The *safety principle* is arguably the central concept in nuclear law [43]. Within the safety principle, there are a number of other principles. These include the *prevention principle* that postulates that, given the special nature of the risks associated with the use of nuclear energy, the primary objective of nuclear law is to promote the exercise of caution and foresight to prevent damage and minimize adverse effects. Another principle is the *protection principle* which postulates that when the risks associated with an activity are found to outweigh the benefits, priority must be given to protecting public health, safety, security, and the environment. The *precautionary principle* also prioritizes protection and the prevention of foreseeable harm as fundamental requirements.

Fundamental safety principles codified in legislation may be applied to a wide variety of activities and facilities that pose very different types and levels of risk. Activities posing significant radiation hazards will obviously require stringent technical safety measures and, in parallel, strict legal arrangements. Activities posing little or no radiation hazard will need only elementary technical safety measures, with limited legal arrangements.

The *security principle* [43] is an underlying principle of the special legal measures that are required to protect and account for the types and quantities of nuclear material that may pose security risks. These measures should protect against both accidental and intentional diversion from the legitimate uses of these materials and technologies. Lost or abandoned radiation sources can cause physical injury to persons unaware of the associated hazards. The acquisition of radiation sources by terrorist or criminal groups could lead to the production of radiation dispersion devices to be used to commit malevolent acts. The diversion of certain types of nuclear material could contribute to the spread of nuclear weapons to both subnational and national entities. It is for these reasons that legal measures regarding physical protection, emergency preparedness, response, and transport, import and export of radioactive material have been adopted.

While safety is of the utmost importance, it is important to carry out a balancing of both the risks and the benefits of exposure. There are situations in which the benefits clearly outweigh the risks, and it is important to not dismiss outright any and all exposure based solely on hazard.

The aforementioned principles are not the only ones used in a nuclear law context. For example, the IAEA Basic International Safety Standards (BSS, *infra*, Sect. 12.4.4.1) represent a broad international consensus on the appropriate handling of radioactive sources to ensure that nuclear-related activities can be conducted in a safe, secure, and environmentally acceptable way. The BSS consists of three sets of publications: the Safety Fundamentals, the Safety Requirements, and the Safety Guides. The Fundamentals establish the fundamental safety objectives and principles of protection and safety, the Requirements set out the requisite conditions that must be met to protect the population and the environment and the Safety Guides provide practical recommendations and guidance on how to comply with the requirements.

The Fundamental Safety Principles are the basis of international and intergovernmental standards of radiation and nuclear safety. They have been established under the aegis of the IAEA and are jointly sponsored by the European Atomic Energy Community (Euratom), the Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the International Labour Organization (ILO), the International Maritime Organization (IMO), the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO), the United Nations Environment Programme (UNEP), and the World Health Organization (WHO).

- The fundamental safety principles are more detailed elements of the safety principle previously discussed:
- The first principle is the responsibility for safety: The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks.
- The second safety principle relates to the role of the government: An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.
- The third safety principle relates to the leadership and management for safety: Effective leadership and management for safety must be established and sustained in organizations concerned with, and facilities and activities that give rise to, radiation risks.
- The fourth safety principle calls for the justification of facilities and activities: Facilities and activities that give rise to radiation risks must yield an overall benefit.
- The fifth safety principle refers to the optimization of protection and safety: Protection must be optimized to provide the highest level of safety that can reasonably be achieved.
- The sixth principle requests the limitation of risks to individuals: Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.
- The seventh principle calls for the protection of present and future generations: People and the environment, present and future, must be protected against radiation risks.

- The eighth principle refers to the prevention of accidents: All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.
- The ninth principle relates to emergency preparedness and response: Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.
- The tenth and final principle refers to protective actions to reduce existing or unregulated radiation risks: Protective actions to reduce existing or unregulated radiation risks must be justified and optimized.

The central underlying principle of nuclear law is safety. If a situation arises in which a law's interpretation is unclear, it is useful to ask which interpretation would lead to the safest outcome. This should of course take into account the beneficial impacts relating to the exposure, but it is a good starting point if confusion arises.

12.4.4 The Legal Hierarchy of Nuclear Law

12.4.4.1 The International Regime

An international regime based on broad international consensus has produced over time a set of recommendations and standards that govern radiation protection. These are not set in stone but have evolved and will still evolve over time as new fundamental scientific insights develop. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) compiles, assesses, and disseminates scientific information on the causal link between incurred doses of radiation and possible adverse health effects outcomes. Its findings are periodically reported to the UN General Assembly (UNGA) and are made available to the public on its website. Since 1950, the International Commission on Radiological Protection (ICRP), a private nongovernmental charity, has been developing internationally agreed-upon recommendations in all areas of radiation protection. The Annals of the ICRP are mostly freely available to the general public.

International radiation protection standards are established under the aegis of the International Atomic Energy Agency (IAEA) with the cosponsoring of other relevant international organizations. Since 1962, the IAEA takes into account UNSCEAR publications as well as ICRP recommendations in order to establish and issue Basic Safety Standards (BSS), which provide fundamental principles, requirements, and recommendations to ensure nuclear safety. The IAEA considers these standards as a global reference for protecting people and the environment and a main contribution to a harmonized high level of safety worldwide. Scientific and technical publications are issued annually and include international safety standards, technical guides, conference proceedings, and scientific reports. They cover the breadth of the IAEA's work, focusing among other topics on nuclear power generation, the use of sealed radioactive sources in medicine, radiation therapy, agriculture, nuclear safety and security, and nuclear law.

The publications by UNSCEAR, the ICRP, and the IAEA are comprised of general principles, mandatory requirements, and binding rules, recommendations, and guidelines. In addition, a growing structure of international treaty obligations and accepted rules of best practices have been developed. Important to note are that these recommendations and standards, while broadly recognized on an international level, are not adopted by all countries in a uniform way. Almost all ICRP recommendations and most IAEA standards are considered to be "soft law" meaning that countries and institutions are encouraged to implement them in regulations and national legislation, without an actual legal obligation to do so.

It is important to note that the national variations in the implementation of nuclear law do not vary from country to country simply due to varying levels of scientific understanding, but is also influenced by political motives and public perception. For example, states that are generally wary of the use of nuclear energy may have a notably different legal framework than states that generally favor the use of nuclear energy, despite these states having essentially the same access to the same scientific information.

There are few hard laws at the international level. Nation states generally retain a large measure of self-determination in regulating nuclear activities within their borders. There is however a substantial international consensus in many areas of radiation protection and consequently in the basic concepts of nuclear law, expressed on the one hand in binding treaties and on the other in rules of soft law, i.e., quasi-legal instruments such as recommendations or guidelines that are strictly speaking not legally binding but are nevertheless widely adopted and may become legally binding in the future.

12.4.4.2 The National and Regional Level

Adherence to international instruments (e.g., conventions and treaties) has both an external and an internal aspect. As a matter of international law, states that take the necessary steps under their national laws to approve (or ratify) such instruments are then bound by the obligations arising out of that instrument in their relations with other States Parties. When this is the case, states need to establish legal arrangements for implementing those obligations internally. Most States require that the provisions of international instruments be adopted as separate national laws. This approach is, for example, reflected in Article 4 of the Convention on Nuclear Safety [46], which states that: "*Each Contracting Party shall take, within the framework of its national law, the legislative, regulatory and administrative measures and other steps necessary to implement its obligations under this Convention.*"

When analyzing nuclear law on a national level, there are basic concepts shared by different states and thus large overlaps in national public law even though national laws remain territorial, meaning only applicable to the state or its nationals. It would be impossible to even summarize, let alone provide a comprehensive overview and compare various nuclear laws in different countries.

The EU is a notable exception to the fragmented incorporation of international binding regulations into national legislation. This is because EU regulations provide a legislative framework that is directly applicable within the EU. The most recent regulatory framework is the consolidated version of the 2013 Directive laying down the basic safety standards for protection against the dangers of ionizing radiation. The Directive establishes uniform basic safety standards for the protection of the health of individuals subject to occupational, medical, and public exposures. It applies to any planned, existing, or emergency exposure situation that involves a health risk from exposure to ionizing radiation. The Directive does not apply to natural levels of background radiation, aboveground exposure to radionuclides present in the undisturbed Earth's crust, exposure of members of the public, or exposure of workers other than air or space crew to cosmic radiation in flight or in space. Exposure to naturally occurring radioactive material (NORM), e.g., in the context of industry or mining activity is regulated if it leads to exposure of workers or members of the public which cannot be disregarded from a radiation protection point of view.

Whether national or regional, it is important to recognize that nuclear law must take its place within the national legal hierarchy. The legal framework in which most states operate consists of several levels. The constitutional level establishes the basic institutional and legal structure governing all relationships within the state. Immediately below the constitutional level is the statutory level, at which specific laws are enacted by the legislative branch of government in order to establish other necessary bodies and to adopt measures relating to the broad range of activities affecting national interests. The third level comprises regulations, detailed and often highly technical rules issued by regulatory bodies to the nuclear industry.

12.4.4.3 Regulatory Bodies

A fundamental element of any national nuclear framework is the creation or maintenance of regulatory bodies with the legal powers and technical competence necessary to ensure that operators of nuclear facilities and users of nuclear material and ionizing radiation operate and use them safely and securely. For example, article 7 of the Convention on Nuclear Safety (CNS) [46] and article 19 of the Joint Convention [47] require the establishment and maintenance of a legislative and regulatory framework to govern the safety of, respectively, nuclear installations and radioactive waste management, identifying a number of functions to be performed by a regulatory body within such a framework.

The central consideration is that a regulatory body should possess the attributes necessary to correctly, self-sufficiently, and independently apply the national laws and regulations designed to protect public health, safety, and the environment. Its tasks can be roughly grouped into four categories: preliminary assessment (establishing requirements and determining whether regulatory control is needed); authorization (licensing and registration, including the prohibition of operations without a license); inspection of nuclear installations and assessment through periodical reviews and enforcing compliance through issuing administrative orders or prohibitions, fines or other penalties. A fifth category, not mentioned in the two aforementioned conventions but considered essential by most regulatory bodies, is the provision of information, including consultation, on regulated activities with the public, the media, the legislature, and other relevant stakeholders. Finally, a regulatory body should be permitted to coordinate its activities with the activities of international and other national bodies involved in nuclear safety.

An example of successful regulation within these parameters can be found in the UK—although the UK is no longer a member of the EU since January 1, 2021—they remain compliant with both article 7 of the CNS and article 19 of the Joint Convention.

12.4.5 Nuclear Liability

A crucial area of nuclear law is nuclear liability. This area is especially important in the context of unplanned emergency exposure to radiation. The occurrence of nuclear and radiological accidents cannot be completely excluded even in situations in which the highest standard of safety has been achieved. All states that engage in nuclear-related activities have generally concluded that general tort law is not an appropriate instrument for providing a liability regime adequate to the specifics of nuclear risks. Tort law is the branch of the law that deals with civil suits alleging negligence, intentional harm, and strict liability, with the exception of disputes involving contracts and is considered to be a form of restorative justice since it seeks to remedy losses or injury from the wrongful acts of others by providing awarding monetary damages to provide full compensation for proved harms. Since civil law is generally designed to cope with large-scale catastrophes, special measures are required, and states have enacted specific nuclear liability legislation.

12.4.5.1 The International Nuclear Liability Regime

The Paris Convention [48], the Vienna Convention [49], the Brussels Supplementary Convention [50], the Joint Protocol [51], the Convention on Supplementary Compensation [52], and the Revised Vienna Convention [53] (hereafter "the Conventions") establish comprehensive regimes for civil liability for nuclear damage. Application of the international nuclear liability regime created by the conventions and the corresponding national legislation will be triggered if an installation or activity causes a nuclear incident.

A nuclear installation must have a person in charge: the operator. In the nuclear liability conventions, the operator is the person—whether this is an individual or any other private or any public entity having a legal personality—designated or recognized as the operator of a nuclear installation by the installation state. The operator, most often the license holder but possibly the owner of the installation, will always be the person responsible (and thus liable) for safety.

The term "nuclear incident" means any occurrence, or any series of occurrences having the same origin, that causes nuclear damage or, but only with respect to preventive measures, creates a grave and imminent threat of causing such damage. Since the occurrence has to cause or threaten nuclear damage, the definition of what constitutes "nuclear damage" is paramount. In general tort law, the concept of compensable damage is well established. If states seek to obtain the benefits of the Conventions, they must accept the definitions.

"Nuclear liability" is understood to be the legal regime based upon the following principles:

- "Exclusive liability of the operator of the nuclear installation concerned;
- "Absolute" or "strict" liability, so that the injured party is not required to prove fault or negligence on the part of the operator;
- Minimum amount of liability;
- Obligation for the operator to cover liability through insurance or other financial security;
- Limitation of liability in time;
- Equal treatment of victims, irrespective of nationality, domicile, or residence, provided that damage is suffered within the geographical scope of the convention;
- Exclusive jurisdictional competence of the courts of the contracting party in whose territory the incident occurs or, in case of an incident outside the territories of contracting parties (in the course of transport of nuclear material), of the contracting party in whose territory the liable operator's installation is situated);
- Recognition and enforcement of final judgments rendered by the competent court in all Contracting Parties." (IAEA Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [47]).

According to Article 1 of the Paris Convention (Third Party Liability), a "nuclear incident" is considered to be "any occurrence or series of occurrences having the same origin which causes nuclear damage."

Furthermore, there must be a causal link between a certain nuclear installation, a certain nuclear incident, and the damage suffered. The burden of proof of the causal link is on the person claiming compensation. The Conventions do not contain any provisions regarding causality. This issue is left to the law of the competent court (i.e., to national law), so states may apply the principles of causality applied in their national law. In most states not all causes of damage are legally relevant; for example, remote causes may not be considered. In many states, the law requires "adequate causality," which means that a cause is only legally relevant if that cause is likely to have directly caused the damage for which compensation is claimed.

The operator of a nuclear installation is held liable, regardless of fault. This concept is sometimes referred to as the channeling of liability. This kind of liability is called strict liability, or sometimes absolute liability or objective liability. It follows that the claimant does not need to prove negligence or any other type of fault on the part of the operator and the simple existence of causation of damage is the basis of the operator's liability. Furthermore, the operator of a nuclear installation is exclusively liable for nuclear damage. No other person may be held liable, and the operator cannot be held liable under other legal provisions (e.g., tort law). Liability is legally channeled solely onto the operator of the nuclear installation. This concept is a feature of nuclear liability law unmatched in other fields of law. With the exceptions of Austria and the USA, all states party to the Conventions that have enacted nuclear liability laws have accepted the concept of legal channeling. Exonerations from this strict liability are limited; the operator being held liable even if the nuclear incident is caused by force majeure (i.e., “an act of God”).

It is also important to note that the financial compensation which results from the liability may be limited in amount because legislators feel that unlimited financial liability would discourage people from engaging in nuclear-related activities. It is important to note that not all states have chosen to limit liability. In the Conventions, claims for compensation for nuclear damage must be submitted within 30 years in the event of personal injury and within 10 years in the event of other damage.

The nuclear liability conventions require that the operators maintain insurance or provide other financial security covering liability for nuclear damage in such amount, of such type, and in such terms as the installation state specifies. Insurance against nuclear risks is quite different in that there are not many nuclear clients in the insurance industry and while the risk is low in frequency, it is potentially very high in severity, resulting in very high amounts to be covered. On an international level international nuclear pools of insurance exist, where insurance companies net their capacity in order to bring together the financial capacities of the entire pool, which is then used to insure domestic civil nuclear risks and to provide inter-pool reinsurance (reciprocation). This pooling principle trickles down to the national level, where the domestic insurance industry is also organized into nuclear insurance pools.

With regard to the compensation rights of those affected by nuclear energy accidents, the Protocols to amend the Paris Convention on Third Party Liability in the Field of Nuclear Energy and the Brussels Convention Supplementary to the Paris Convention have entered into force on 1 January 2022. The revised conventions combined ensure that those suffering damage resulting from an accident in the nuclear energy sector will be able to seek more compensation—the operator liability will be of at least EUR 700 million under the Paris Convention and the public funds provided under the Brussels Supplementary Convention will complement up to EUR 1.5 billion, a sharp increase from the previous 5 million Special Drawing Rights (SDR) (approximately EUR 6 million as of 13 December 2021) and SDR 125 million (approximately EUR 155 million as of 13 December 2021), respectively. The revised Paris Convention also provides now for a minimum of EUR 70 million and EUR 80 million in case of accidents at low-risk installations and during the transport of nuclear substances, respectively. A total of 16 countries will be parties to the amended Paris Convention, covering 105 operating reactors and 7 under construction, out of a total of 442 operating reactors worldwide and 51 under construction. Of those countries, 13 are also parties to the amended Brussels Supplementary Convention (NEA COM 2021).

Finally, with regard to jurisdiction, national procedural law(s) across countries may indicate several courts to have jurisdiction when dealing with claims arising out of a nuclear incident with transboundary or international effects—meaning several courts could be allowed to claim competence to seize proceedings. The more complicated the different causes and effects, the more parties internationally involved and the larger the effects of the contamination, the greater the selection of potentially competent courts. For this reason, the Conventions provide, firstly, that only courts of the state in which the nuclear incident occurs, have jurisdiction and, secondly, that each member state party to the Conventions shall ensure that only one of its courts has jurisdiction in relation to any one nuclear incident. The concentration of procedures within a single court not only creates legal certainty but also excludes the possibility that victims of nuclear incidents will go “forum shopping” and seek to submit claims in states where their claims are likely to receive more favorable treatment.

12.4.5.2 Transboundary Implications of Radiation Incidents

If an activity or facility could cause public exposure in neighboring states through the release of radioactive substances to the environment, the regulatory body in the state of the licensee should take steps to ensure that the activity or facility will not cause greater public exposure in neighboring states than in the state of the licensee [55]. The concept of neighboring states does not require that these states share a border.

The Convention on Early Notification of a Nuclear Accident (the Early Notification Convention) [56] and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (the Assistance Convention) [57] cover situations in which an accident involving activities or facilities in one state have resulted or may result in a transboundary release that could be of radiological safety significance for other states. In this context, legally binding obligations as adapted in national legislations may arise for radiobiologists, requiring them to notify, directly or through the IAEA, those states which are or may be affected by a nuclear accident. The nature of the nuclear incident, the time of its occurrence and its exact location should be promptly provided to those States affected in order to minimize the radiological consequences in those states.

12.4.5.3 Radiation Damage under General Tort Law

The nuclear liability conventions cover neither radiation damage caused by radioisotopes used for scientific, medical, commercial, and other purposes nor radiation damage caused by X-rays. This is because the use of radioisotopes and X-ray equipment does not present risks comparable to those for which the conventions were designed. The regime created by the conventions is intended for extraordinary nuclear risks only.

Even though experience has shown that radioisotopes and medical irradiation equipment can also cause serious damage if not handled properly, most states deal with liability for radiation damage caused by radioisotopes and X-rays under general tort law. States are free to enact, at the national level, special liability laws for damage caused by these types of exposure, providing for modified strict liability where the principle of liability without fault is maintained but the person liable may be exonerated if they can prove that they could not prevent the occurrence of the damage even though they complied with all radiation protection requirements and if they prove that any equipment used was not defective.

In a medical context, harm caused could potentially amount to a breach of the duty of care that is owed to a patient from a medical professional or radiologist. If the person liable owes a duty of care to the patient, it must be proven that this duty was breached, resulting directly in the harm suffered by the patient. Where the breach is caused by gross carelessness, the liable party may be criminally negligent.

12.4.6 Special Legal Issues Related to the International Radioprotection System

12.4.6.1 Optimization of Protection

One of the key principles of the radiation protection system recommended by ICRP is the principle of optimization of protection. The aim is to select the best protection option under the prevailing circumstances in order to keep the likelihood of exposure, the number of people exposed, and the magnitude of the individual doses incurred, all "as low as reasonably achievable" often abbreviated to the acronym "ALARA," taking into account economic and societal factors alongside health factors.

It is important to stress that "ALARA" does not simply mean "as low as reasonably achievable" in the sense that it should always be the "very lowest" level of radiation exposure that can technically be achieved. "ALARA" should rather be the "best" protection option, nuanced and well-reasoned, where the highest level of safety that can be achieved from a health perspective, always needs to be balanced by social, environmental, and economic considerations.

Standards are established and safety measures prescribed in order to ensure that facilities and activities with radiation risks achieve the highest level of safety throughout the lifetime of the facility or duration of the activity, without unduly limiting its utilization or usefulness. In order to determine whether radiation risks are at a level as low as reasonably achievable, any and all risks, whether arising from normal operations, abnormal conditions, or accidents, must be assessed using a graded approach that is periodically reassessed throughout the progression of the activity or lifetime of the facility.

The optimization of protection requires careful judgment on the basis of scientific fact that is generally highly influenced by subjective appraisal tailored to individual situations, which makes it a difficult principle difficult to implement uniformly and consequently legally. The relative significance of various goals, events, and factors have to be judged, including the number of people (both workers and the general public) who may be exposed to radiation, the likelihood of exposure, the magnitude and the radiation doses likely to be received as a result of foreseeable and unforeseeable events, as well as the economic, social, and environmental factors involved with the installation or activity.

12.4.6.2 The ICRP's International System of Radiological Protection

The ICRP recommends, develops, and maintains the International System of Radiological Protection, based on an evaluation of the large body of scientific studies available to equate risk to received dose levels.

> The system's health objectives are relatively straightforward "*to manage and control exposures to ionizing radiation so that deterministic effects are prevented, and the risks of stochastic effects are reduced to the extent reasonably achievable*" (ICRP Publication 103).

To this end, the ICRP has established a system of radiological protection with three main principles: justification, optimization of protection, and individual dose limitation that apply to planned, emergency, and existing exposure situations. Planned exposure situations are situations involving the deliberate introduction and operation of sources of radiation, either anticipated (normal exposures) or not anticipated to occur (potential exposures). 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 requiring urgent action. Existing exposure situations are exposure situations that already exist when a decision relating to control has to be taken, including prolonged exposure situations after emergencies. The ICRP considers exposure to cosmic radiation to be an existing exposure situation.

The first two principles, justification and optimization of protection are source-related and apply in all exposure situations. The principle of justification states that any decision that alters the radiation exposure situation should be more beneficial than detrimental. The principle of optimization of protection states that the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept As Low As Reasonably Achievable (ALARA), also taking into account economic and societal factors. The third principle concerning individual dose limitation is individual-related and applies in planned exposure situations: the total dose to any individual from regulated sources in planned exposure situations other than medical exposure of patients should not exceed certain appropriate limits.

The ICRP further distinguishes between three categories of exposures: occupational exposures, public exposures, and medical exposures of patients. Occupational exposure is defined as all radiation exposure of workers incurred due to their work. ICRP limits the use of "occupational exposures" to radiation incurred at work in situations that can reasonably be regarded as being the responsibility of the operating management. The employer has the main responsibility for the protection of workers. Public exposure encompasses all exposures of the public other than occupational exposures and medical exposures of patients. The component of public exposure due to natural sources is by far the largest, but this provides no justification for reducing the attention paid to smaller, but more readily controllable, exposures to man-made sources. Exposures of the embryo and fetus of pregnant workers are considered to be public exposures and regulated as such.

While dose is a measure of the total amount of radiation received, the dose limit is a value of the effective or equivalent dose to individuals that may not be exceeded in activities under regulatory control. The regulatory body sets the dose limits for various activities. These dose limits are sometimes found in the nuclear laws, but more often in the accompanying and more detailed regulations, where regulatory bodies principally rely on IAEA publications.

12.4.6.3 Individual Dose Restrictions

Restricting an individual's radiation dose is another key factor of the international radiation protection system. Restrictions include dose limits, dose constraints, and reference levels of dose. Each of these restrictions has different legal implications.

> The *dose limit* is the value of dose to individuals from planned exposure situations that shall not be exceeded. A *dose constraint* is a prospective and source-related restriction on the individual dose from a source, which provides a basic level of protection for the most highly exposed individuals from a source, and serves as an upper bound on the dose in optimization of protection for that source.

Table 12.1 Recommended dose limits in planned exposure situations

Type of limit	Occupational	Public
Effective dose	20 mSv/year, averaged over defined periods of 5 years	
Annual equivalent dose in:		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	–

For occupational exposures, the dose constraint is a value of individual dose used to limit the range of options, both short- and long-term, considered in the process of optimization. For public exposure, the dose constraint is an upper limit on the annual doses from the planned operation of any controlled source that members of the public should not exceed. In emergency or existing controllable exposure situations, a *reference level* is established to represent the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimization of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration.

Dose limits are not uniform, neither in concept nor in the quantities that they are expressed. The three dose quantities used for establishing dose limits are the absorbed dose, the equivalent dose, and the effective dose. The absorbed dose is a measurable, physical quantity expressing the amount of energy deposited by radiation in a mass. The equivalent dose is a weighted absorbed dose designed for specific radiation protection purposes and is calculated for individual organs while the effective dose, which is also designed for specific radiation protection purposes, is calculated for the whole body. Dose limits may vary depending on factors such as pregnancy. It is worth noting again that dose limits do not apply to emergency, existing, or medical exposures. Dose limits only apply to occupational, public, and planned exposure. The current dose limits set out by the ICRP in Publication 103 are as set out in Table 12.1 below.

Dose limits set by the ICRP are not hard law but most countries have implemented these limits into their national legislation making the exceeding of dose limits illegal. The industry may also choose to set dose limits for their workers even lower than those required by law to both ensure the safety of their employees and reduce the likelihood of lawsuits.

12.4.6.4 Radiation Workers

Radiation workers are obviously more at risk to be exposed to radiation than the average individual and dose limits for occupational exposure are different from dose limits for public exposure, specifying an upper limit and a relevant time span.

In case of a nuclear emergency, workers will likely be exposed to significantly higher doses, often much higher than the annual recommended dose limit. A very careful assessment will have to be made weighing the rescuer's own risk versus a clear benefit to others.

The ALARA principle encourages practitioners and other individuals who have an influence on radiation dosage to limit dosage as much as practically possible, even when accounting for the benefits the exposure situation might bring. This also means that if the exposure does not present a direct and sufficient benefit, it should be avoided. In order to optimize protection for radiation workers, the duration of the exposure should always be minimized while the distance between the source of the radiation and the individual should be maximized. A third essential factor is shielding.

The legally binding obligations related to occupational radiation protection are established in the Radiation Protection Convention No. 115 adopted by The General Conference of the International Labour Organization [58]. This Convention, which has been ratified by most countries, applies to all activities involving exposure of workers to ionizing radiations in the course of their work and who, in applying its provisions the state party's competent authority, have to consult with representatives of employers and workers.

12.4.6.5 Medical Use

Sources of ionizing radiation are essential to modern healthcare as they span a range of purposes, such as the sterilization of disposable medical supplies, central to combating disease [59]. To give a more recent example, China has optimized the use of radiation to cut down sterilization times from 7 days to just 1 in order to combat the COVID-19 pandemic [60]. Radiology is also a vital diagnostic tool; CT and X-rays have been crucial to healthcare in terms of diagnostic precision, which in turn improve treatment response.

However, as ionizing radiation can be detrimental to living organisms, humans included, it is essential that sources of ionizing radiation be covered by measures to protect individuals. Medical treatment involving planned exposure to ionizing radiation can only take place if the patient has agreed after being carefully informed about the risks.

Radiation exposures of patients occur in diagnostic, interventional, and therapeutic procedures. There are several features of radiological practices in medicine that require an approach that differs from radiological protection in other planned exposure situations. The exposure is intentional and for the direct benefit of the patient. Particularly in radiotherapy, the biological effects of high-dose radiation, e.g., cell killing, are used for the benefit of the patient to treat cancer and other diseases. The medical uses of radiation therefore require separate guidelines.

A relatively recent topic of discussion is that of adventitious exposure, i.e., unintended exposure happening as a result of primary, intended exposure. A patient undergoing therapeutic exposure to ionizing radiation—exposure that is considered to be beneficial, contributing to a positive medical outcome—probably will suffer to some extent, effects that are neither intended nor desired because these are an unavoidable by-product of radiotherapy procedures. Adventitious exposure can occur in any part of the body and cause secondary cancers as a malignant result of radiotherapy, the effects remaining latent, manifesting only after the treatments. It is important to distinguish that cancer forming due to adventitious exposure is not a metastasis of the original malignancy, but rather a primary malignancy in itself. The incidence of such cancers is being investigated worldwide, also by UNSCEAR, and may contribute to litigation initiated by patients or their next of kin against radiobiologists or other radiation specialists in the medical field. A deep understanding of this complex mechanism is still evolving, but the medical professional would do well to document—either by measurement or estimation—the scenario of adventitious exposure situations through dosimetric quantities or suitable proxies. It may even prove to be necessary to dutifully inform and obtain explicit patient agreement on the subject.

Most countries have regulations to guide the medical professional involved with treatment that includes medical exposure of a patient to ionizing radiation in order to protect both the professional and the patient. In the EU, Council Directive 2013/59/Euratom Chapter VII [61] centers the relevant articles 55 and 56 once again around the principles of justification and optimization. In the assessment and justification of the use of radiology with any specific patient, the practitioner should consider all relevant aspects of their medical history and decide, with feedback and consent from the patient, the radiation therapy most suited to that individual patient.

12.4.6.6 Exposure to Cosmic Rays

Cosmic rays at ground level are not considered to warrant regulatory control. Mankind has been exposed to—and has evolved with—radiation from the universe reaching Earth since the beginning of time. However, at high altitudes, where cosmic rays are less attenuated by the atmosphere or, even higher, by the Earth's magnetic field, they undoubtedly pose a risk to people and equipment because of the very high energies involved. As a consequence, astronauts and aircraft personnel need to be well informed about these exposure risks during the course of their careers and possible consequences and outcomes as a result.

Disregarding the Space Treaties that arguably do not really deal with exposure to ionizing radiation, the protective framework for astronauts in this context is not regulated by international law, but rather designed and governed by the space agencies by which they are employed, on the basis of an ever-evolving scientific insight and assessment. All major space agencies have very stringent safety precautions in place, specifying dose, dose rate, and career limits for their astronauts in order to make sure there is no statistical risk of radiation exposure-induced death (REID) and other adverse effects. Even though astronauts are generally extremely healthy and are unlikely to suffer health effects at a level worse than that of the general population, the advent of deep space travel, notably the Moon and Mars missions planned in the near future, will likely expose them to high fluxes of solar energetic particles and heavy ions, in possibly problematic amounts. Radiation mitigation strategies, shielding and careful mission planning, and astronaut selection will prove to be crucial to attempt these types of interplanetary exploratory missions. Being continuously monitored and genetically screened for suitability may however create some legal issues as well. Not only are privacy issues imaginable with the extreme scrutiny astronauts are subjected to, but unequal treatment and an imbalance in career opportunities due to individual genetic predisposition to adverse health effects from ionizing radiation may at some point also become an object of contention, as is discussed more in depth in Sect. 12.3.8 on emerging occupational challenges from new methods to determine individual radiosensitivity (*supra*).

Guidance and protection for other jobs at slightly lower altitudes are much more regulated. Airline pilots and personnel—and even frequent flyers—repeatedly expose themselves to ionizing radiation, primarily from charged particles and therefore require employment protection. Compared to astronauts, aircraft personnel make up a substantially larger group of radiation workers, inspiring governments to implement special mandatory protection measures. For example, Directive 96/29/Euratom 1996 requires appropriate radiological protection of aircrew. Article 42 of the Directive obliges member states to regulate the sector, specifically regarding the exposure to cosmic radiation at flight altitudes. As a result, each member state is obliged to force airline companies to take account of exposure to cosmic radiation of aircrew who are liable to be subject to exposure to more than 1 mSv/year. EU airline companies need to record a continual assessment of the exposure of the crew concerned and use this information when organizing working schedules with a view to reducing the doses of highly exposed aircrew. Aircraft personnel needs to be informed of the health risks their work involves and female aircrew in particular, when pregnant, will have the terms of her employment adapted to ensure that the equivalent dose to the child to be born is ALARA and that it will be unlikely that this dose will exceed 1 mSv during at least the remainder of the pregnancy. As soon as a nursing woman informs her employer of her condition, she cannot be employed in work involving a significant risk of bodily radioactive contamination. This is of course not to say that female airline crew are the only radiation workers protected through nuclear law; different rules for pregnancy, varying from country to country, are applicable for workers in other nuclear industries.

12.5 Legal Imputation of Radiation Harm to Radiation Exposure Situations

12.5.1 Legal Actions Resulting from Radiation Exposure Situations

Legal action based on radiation harm, i.e., legal proceedings or a lawsuit, generally requires two elements to succeed; attribution and imputation. First, a causal link must be established; a certain health effect needs to be attributed to a certain radiation exposure using objective factual evidence. Second, there needs to be imputation, meaning someone's responsibility for the radiation harm needs to be determined. In a legal context, imputation means placing the responsibility for the physical injury (actual or potential ill effects) that is attributable to the radiation exposure, on another (natural or legal) person. While "attribution," meaning establishing the factual link between a nuclear incident and a health effect and "imputation," meaning ascribing responsibility for the radiation harm are closely related in that they both attempt to establish a causal link, they have often been used as synonyms, causing confusion. Examples range from the use by the International Labour Organization (ILO), International Atomic Energy Agency (IAEA) to the World Health Organization (WHO).

> When attribution between the incident and the effect is established, imputation is crucial to allow for subsequent legal actions such as charging, indicting, and prosecuting—if a criminal element is involved—or simply initiating a civil suit if another form of negligence can be demonstrated. The end goal for the plaintiff is to obtain reparation for damages incurred.

Attribution and imputation both generate controversy and two basic challenges dominate the issue. The first challenge is the attribution of specific health effects to a specific radiation exposure situation, which requires qualified experts to demonstrate that a factual occurrence can be causally linked—meaning without a doubt—to radiation harm. The second challenge is of a more formal nature; how to proceed with relevant legal actions consistent with the legal practice in the applicable jurisdiction or legal system. In high-exposure incidents with obvious harmful effects, this is relatively straightforward. On the other hand, a challenge arises in situations involving low to very low radiation doses. This issue is amply discussed in the literature [62–64] but no clear solution, let alone a consensus between experts, has been found yet.

12.5.2 Attribution and Inference of Health Effects to Radiation

The attribution of health effects to radiation means no more than factually linking the health effects of radiation exposure to objective and indisputable evidence of any given radiation exposure situation. When establishing attribution, there can generally be no reasonable doubt between the cause and the health effect. When moving away from a high-dose, high-probability scenario, in cases where low or lower doses are concerned, the lines become blurred and direct attribution can be problematic. As a consequence, in low-dose scenarios the causal link often needs to be inferred, meaning a reasonable conclusion needs to be reached on the basis of evidence and experience. In contrast to attribution, inference entails the process of drawing conclusions from subjective conjectures involving indirect conclusions based on scientific observations and reasoning on radiation risks, while allowing an element of uncertainty. The discussion involving the attribution of health effects to radiation and the inference of radiation risks is closely followed on an international level by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (UNSCEAR [65] Report to the General Assembly with Scientific Annexes). UNSCEAR, which has been compiling and discussing decades of case material, scientific research, and expert opinions on the subject, periodically reports its findings to the United Nations General Assembly [66]. The United Nations Environment Program (UNEP) has summarized the progressing UNSCEAR insights and has made an abridged version available to the general public, in an illustrated volume [67] containing the illustrations that are used in this chapter. The UNSCEAR findings are simplistically condensed in a dose–response relationship, a graphical representation of the probability that people would suffer health effects and the radiation doses they have incurred, shown in Fig. 12.1.

UNSCEAR has highlighted the importance of distinguishing between two types of effects (see yellow ellipses in

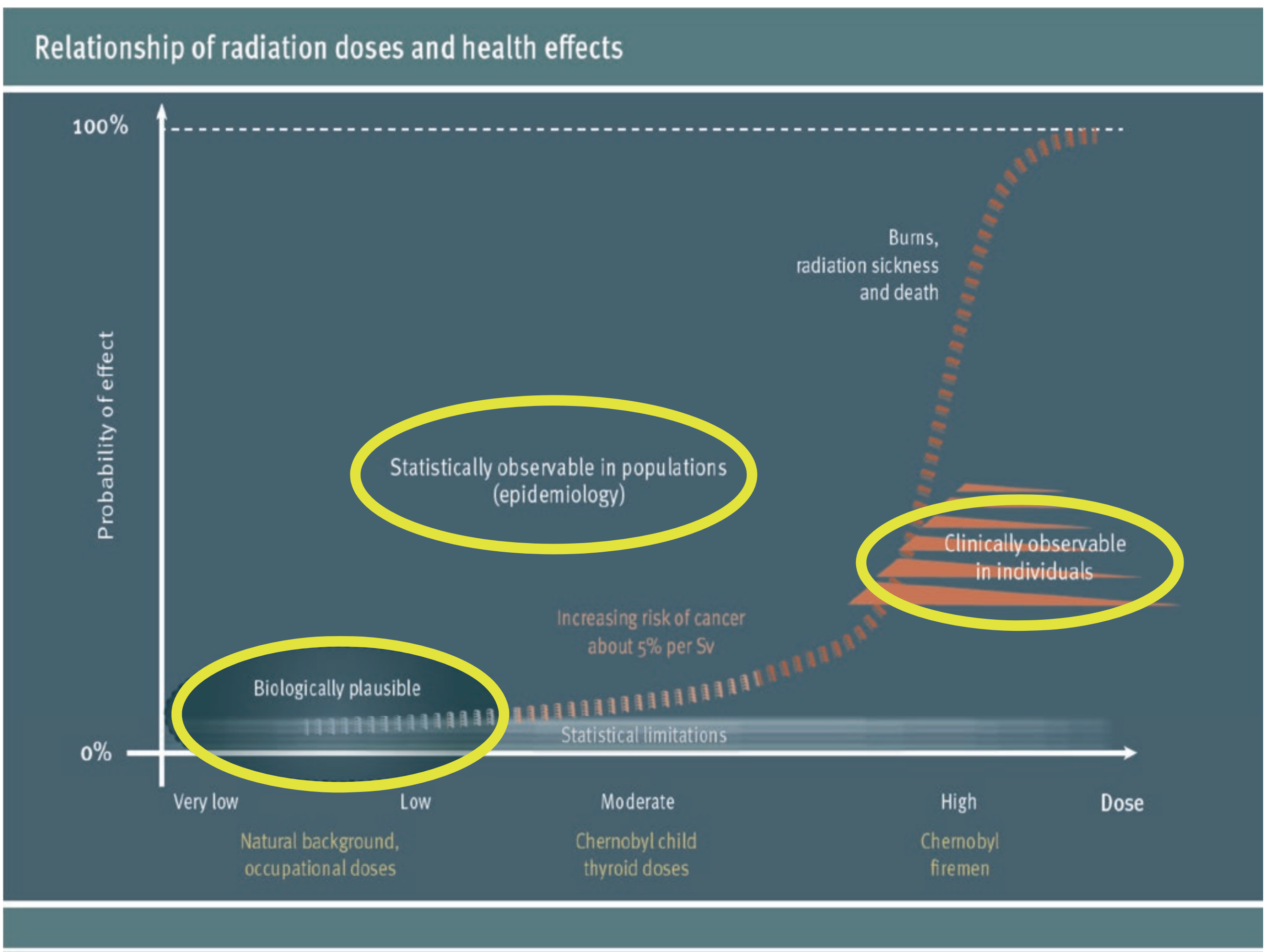

Fig. 12.1 Adapted from UNSCEAR 2012, Annex A Schematic of the relationship between dose, additional to that from typical exposure to natural background radiation, and probability of occurrence of health effects, Fig. AV-I p68

Fig. 12.1). Purely observational health effects in exposed individuals and populations will lead to attribution if the health effect to radiation exposure situation is observed and then attested. On the other hand, plausible health effects for which occurrence is likely conceivable but not directly verifiable, only allow one to infer health effects from known risks, but without clear attribution.

In the figure, the doses on the *x*-axis are expressed from very low to high. A "high dose" indicates an effective dose around 1 Sv and up, many orders of magnitude higher than the annual levels of natural background radiation. A "moderate dose" is situated between 100 mSv and 1 Sv, while a "low dose" is in the tens of mSv, and a "very low dose" is around 1 mSv.

Note too that the probabilities on the *y*-axis are expressed in percentages between 0% and 100%, where 100% corresponds to the certainty that the effect will occur and 0% corresponds to the certainty that the effect will not occur. In between these values, probabilities need to be calculated, which can be done in two ways. Frequentist probabilities are most often used in the high-dose range and take into account the verifiable existence of radiation health effects, defined as the limit of the relative frequency of incidence of the effect in a series of certifiable epidemiological studies. Frequentist probabilities are based on fact. In low-dose ranges, clear-cut evidence and unambiguous studies are scarce and a frequentist probability is out of the question. The solution then would be to include subjective—or "Bayesian"—probabilities, that are expressed as an expectation that radiation health effects could occur, but these are not so much based on and quantified by scientific reasoning as on an expert's judgment that may arguably not be substantiated by the frequency or propensity that the effects actually occur. In other words, reasoned conjecture.

12.5.3 Attesting Effect Occurrence

The attribution of radiation harm is an essential component of any legal action. A professionally qualified expert witness should provide clear evidence on the occurrence of radiation effects, caused by a radiation incident, by formally declaring that a causal effect exists. It is obviously not necessary for an expert to have witnessed first-hand the incident at the origin of a radiation-related lawsuit, but he or she does need to be a specialist in radiation effects and able to offer, without reasonable doubt, an expert opinion after considering the chronology of events and factual occurrence of the causes and the effects.

Crucially, the type of expert a plaintiff would rely upon to bring evidence to the case is related to the dose and dose rate, or more precisely the dose–response relationship connected to the incident. This of course is related to the factual observability and thus the scientific attestability of the effects—ranging from attributing to inferring. In a high-dose scenario, the effects are most likely clinically observable, easily attributable and therefore diagnosable in exposed individuals by a qualified expert radiopathologist. In the region of moderate doses, the effects are not directly attributable in individuals because similar effects can occur due to other causes, but they are statistically consistent with the background incidence of the effect that has been studied in certain population cohorts. This incidence can be mathematically quantified as a probability and attested by a radioepidemiologist. Both radiopathologists and radioepidemiologists rely on frequentist probabilities with a high degree of certainty. In the low to very low-dose range, most effects are neither observable nor attributable and thus their occurrence is not attestable with any reasonable certainty. However, a case can be made that the effects of a low-dose incident may be biologically plausible and therefore risk and potential radiation harm could be inferred through the personal judgment of radioprotectionists by assigning probabilities. The probabilities offered in these low-dose cases by radioprotectionists are arguably less objective than the frequentist probabilities demonstrated by radiopathologists and radioepidemiologists since they are skewed towards expert opinion based on experience rather than indisputable scientific fact. This is visible in Fig. 12.2.

Radiopathologists, radioepidemiologists, and radioprotectionists can all be qualified expert witnesses in the context of legal action, the first attesting the factual occurrence of health effects that can be diagnosed in individuals, the second attesting the factual occurrence of radiation health effects that can be estimated in population cohorts using statistics on the incidence and distribution of diseases associated with radiation exposure, and the third by inferring radiation risks from theory rather than fact. Radiobiologists are a fourth group of scientists that could be situated somewhere between radiopathologists and radioepidemiologists. A radiobiologist has expertise in the branch of biology concerned with the effects of ionizing radiation on organisms, organs, tissues, and cells which can be useful—without directly attesting the factual occurrence of biological changes in an individual—to demonstrate probable effects on tissue after radiation exposure by extrapolating data collected during the study and analysis of specialized bioassay specimens, hematological and cytogenetic samples.

12.5.4 Legal Consequences

The ability to attribute health effects to specific exposure situations and to attest their occurrence by means of a qualified expert witness has a direct influence on the chances of successful litigation if the radiation harm can be clearly

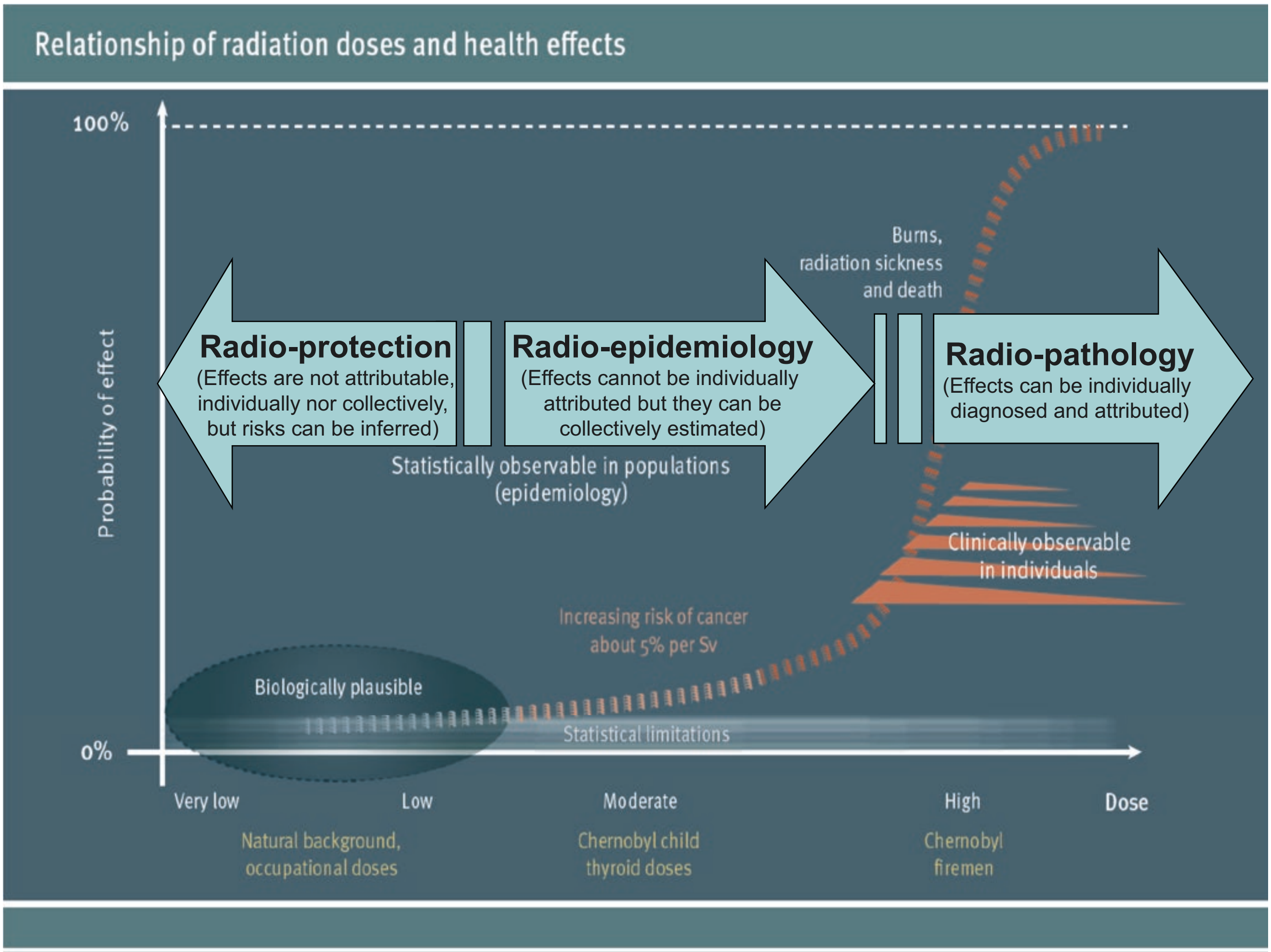

Fig. 12.2 Adapted from UNSCEAR 2012, Annex A Schematic of the relationship between dose, additional to that from typical exposure to natural background radiation, and probability of occurrence of health effects, Fig. AV-I p68

attributed to an incident, imputed to the persons responsible and subsequently compensation awarded to the victims by a court of law. Physical injuries and harmful effects inflicted by those who have caused the exposure, if proven, allow radiation workers or the general public to bring a lawsuit against employers, licensees of nuclear installations, or even the regulatory authorities in the event of a lack of oversight or effective control.

The legal playing field however is not quite level. Legislation and regulatory frameworks that deal with the attribution of radiation health effects are inhomogeneous, sometimes incoherent, and inconsistent among countries and even within countries. A major fault line exists between legal systems based on jurisprudential legislation and those who rely on detailed codified legislation. A comparison of case law exceeds the scope of this chapter, but—at the risk of being overly coarse—we could state that jurisprudential legal systems that employ a case-by-case approach are generally more flexible and provide a higher degree of legal certainty for the plaintiff. Jurisdictions that rely on codified legislation are not bound by legal precedent, placing a high degree of autonomy on the court in applying the rule of law, which can lead to less predictable results.

Figure 12.3 attempts to broadly define what would be feasible when litigating the following situations.

In the high-dose region, individual health effects are clinically attributable and attestable, and imputation of harm incurred by the affected individual is therefore straightforward. Attribution is clear; imputation is often directly linking the individual suffering radiation harm to the responsible person and a classic lawsuit, where civil legal action by one person or entity against another person or entity has a high chance of success.

In the moderate dose region, increased incidences of harmful effects in population groups are epidemiologically attributable and attestable and imputation to the responsible person is therefore feasible. When dealing with the harmful

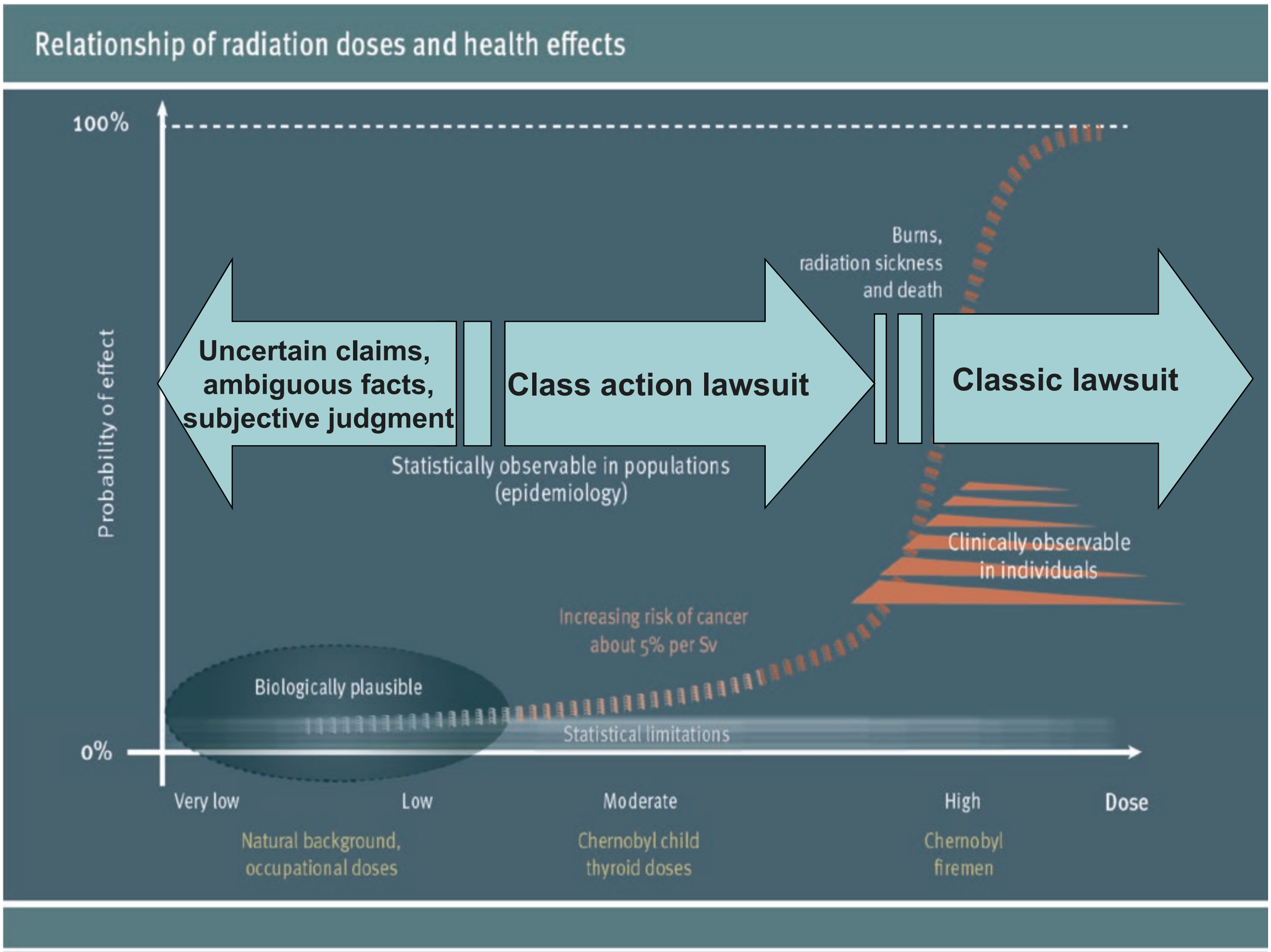

Fig. 12.3 Adapted from UNSCEAR 2012, Annex A Schematic of the relationship between dose, additional to that from typical exposure to natural background radiation, and probability of occurrence of health effects, Fig. AV-I p68

effects of moderate doses, a collective or group imputation is more logical, e.g., via a class action lawsuit where the plaintiffs are more likely than not a group of people presenting a collective claim.

In the low-dose region, radiation harm is neither attributable nor attestable on an individual or collective level, but some radiation risk might be inferred. From a legal perspective, claims based on a low dose or low dose rate exposure are uncertain. Since radiation harm might not yet have presented itself or, if present, might be quite removed in time from the alleged exposure situation, a court might struggle with establishing, beyond a reasonable doubt, a causal link between the exposure situation and any health effects allegedly suffered by the plaintiff. The problem presented here is one of objectivity. The cause cannot be attested, the harmful result is only inferred considering theoretical risk and perhaps statistical probability, and any judgment based on these ambiguous facts would have a high degree of subjectivity.

12.5.5 Next Steps

The scientific consensus on health effects attributable to radiation exposure—consensus that in itself is not entirely uniform and still progressing—should serve as a basis for the development of legal instruments in order to have a more uniform treatment of legal actions. In particular, the issue of legal imputation when considering low dose rates should be carefully considered. This issue has not yet crystallized in any type of universal approach, in large part given the fundamental differences between case-based and codified legal systems. The scientific community is eager to provide legal experts with guidance based on the progressing insight into the attribution of radiation effects following radiation exposure situations.

Given the cultural, regulatory, and legislative differences among countries, two fundamental objectives stand out. First, it seems imperative to foster a common legal understanding of cause and effect when dealing with radiation harm and radiation exposure situations. From a scientific perspective, this seems feasible, and if adopted by the legal community, this would greatly enhance legal certainty. Second—and perhaps even more optimistically—the establishment of a universal scientific and legal consensus to direct the application of the law in any situation would reduce uncertainty even further and might even benefit the development and harmonization of different national legislations. In reality however "the law" is not a uniform concept and nations, courts and judges, prosecutors and lawyers will always want to look at the facts of any individual case, assess the differences and exceptions to the rules if there are any and, in general, assert their independent reasoning. Today, the road ahead for the legal community dealing with nuclear law seems long and far from determined.

12.6 Social and Psychological Issues Associated with Radiation Exposure

12.6.1 Introduction

Human behavior is primarily driven by perception and not by facts [68]. In practice, this pattern is clearly demonstrated also in people's behavior related to ionizing radiation. For instance, exposure to the medical application of ionizing radiation is highly acceptable for most people, while food irradiation used to increase the safety of food may be unacceptable for many people, although in the first case the patient may receive a relatively high radiation dose and in the second case the consumer will not receive any radiation due to the sterilization [69, 70].

Likewise, 10 mSv received as a worker's exposure or 10 mSv received during an accidental release of radioactivity to the environment may cause different behavior. This section examines the social and psychological aspects of radiation exposure. First, we will explain the phenomena of radiation risk perception and second we will identify and discuss determinants of health and radiation protection behavior. Finally, we will conclude this chapter with radiation risk communication advice for experts in radiobiology in order to be able to communicate effectively and help people to make informed decisions related to radiation risks.

12.6.2 Perception of Radiation Risk

Risk perception mainly denotes the ways individuals think and feel about the risks they face [71–73]. Radiation risk perception has been extensively studied, for example, in the context of nuclear power [74–76], nuclear testing [77], radioactive waste [78], radon [79], food sterilization by irradiation [80], and nuclear accidents [81]. It is interesting that people perceive radiation risks differently, depending on the origins of this radioactivity, and the contexts in which it is encountered.

In order to demonstrate diversity in radiation risk perception, we present the results of a public opinion survey conducted in a high radon-prone area in Belgium [82]. Figure 12.4 illustrates how residents of radon-prone areas think and feel about environmental and radiation risks. It shows that residents living in radon-prone areas in Belgium perceive the risk from environmental pollution as the highest potential risk to their health within the next 20 years, followed by the risk of a climate crisis. Among risks related to

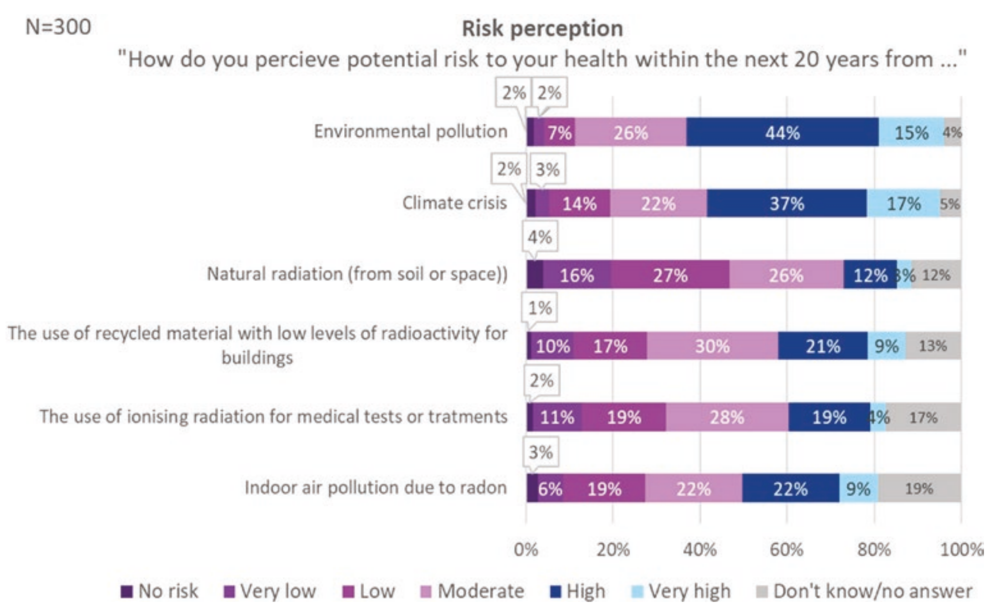

Fig. 12.4 Perception of environmental and radiation risks by residents of high radon-prone area in Belgium, 2021 [82]

radon and naturally occurring radioactive material, the risk of indoor air pollution due to radon is perceived as the highest potential risk to their health within the next 20 years, followed by the use of recycled material with low levels of radioactivity for buildings. The lowest risk for health within the next 20 years is perceived to come from natural radiation from the soil or from space. Interestingly, in this 2021 survey, the risk of medical applications of ionizing radiation is perceived as one of the lowest radiation risks by residents of radon-prone areas in Belgium, although medical exposure presents the most significant dose in Belgium.

Research also shows that experts and the general public often disagree about the potential danger posed to their health by nuclear waste, an accident in a nuclear installation, natural radioactivity, medical X-rays, or the Daiichi nuclear accident in Fukushima [83]. In the study of Perko [84], the public had significantly higher risk perceptions of all radiation risks when compared to experts, with the only exception being medical exposure. However, expert opinion and lay perception need to be perceived as complementing rather than competing with each other [85]. Remarkably, empirical results show that experts too do not think and feel the same about radiation risk. When a distinction was made between experts that received a dose of more than 0.5 mSv due to their professional exposure, and those who did not, those who were exposed to more than 0.5 mSv perceived the risk of radiation waste and an accident in a nuclear installation significantly lower than their colleagues did. Similarly to this, they also did not agree about risks from nuclear accidents in Japan. On the other hand, the employees receiving a dose higher than 0.5 mSv had significantly higher risk perceptions of natural radioactivity and medical use of ionizing radiation than their colleagues. These results can be explained by the characteristics of risk, suggesting that familiarity with risk, knowledge, personal control, and voluntariness decrease risk perception.

Characteristics of risk and their impact on (un)acceptability have been studied and identified by scholars using a psychometric method [68, 86, 87]. Studies of risk perception examine the opinions people express when they are asked, in various ways, to characterize and evaluate hazardous activities and technologies [85, 88]. The method is based on a number of explanatory scales corresponding to various risk characteristics, which are an explanation of contextual traits that people use when they make decisions related to risks. Some of these scales involve traits focusing on whether the risk has an influence on children, whether it is involuntary or not, whether people are familiar with the risk or it is new to them, whether the risk has a catastrophic potential, whether it can cause delayed or immediate consequences, whether the risk is already known to science or not. Table 12.2 demonstrates the characteristics of risks, their influence on risk (un)acceptance, how they can be explained in a scale from maximum to minimum, as well as providing descriptive examples of radiation risk acceptance as hypothetical scenarios.

12.6.3 Determinants of Health and Radiation Protection Behavior

Research shows that only one person in five is prepared to take health-related actions at any given time [89, 90]. Radiation protection behavior is not an exception to this finding. Authorities and other radiation protection actors are often challenged with what has been termed a "value-action gap." This gap refers to a situation where the values or attitudes of an individual or a group of people do not correlate with their actions; a positive attitude towards good health does not lead to an action to improve/protect health [91].

For instance, testing for radon and remediating your home if radon concentrations are too high are scientifically and technically straightforward actions. However, empirical studies indicate that testing and remediation are generally low among those exposed to high indoor radon, although these persons have relatively high-risk perceptions [92], the cost of radon mitigation measures for most homes is similar to that of common home repairs, and this cost is often an eligible expense covered by national health care programs [93–95].

A similar value-action gap is repeatedly reported in studies related to the behavior of people before, during, and after nuclear or radiation emergencies. For example, the study of Turcanu et al. [54] conducted in Belgium, Norway, and Spain, provides empirical evidence that people in the analyzed countries have difficulties complying with some protective actions in case of a nuclear accident. Leaving children at school, avoiding the use of phones during an emergency, not rejecting food produced in affected areas even when it satisfies legal norms or taking iodine tablets when not needed, were identified as the most critical protective actions with which a large number of people would not comply [96].

This raises the question what determinants of health and radiation protection behavior can be discerned. Different determinants have been studied in the context of health behavior models. The most known and tested models in the radiation protection field are the Protection-Motivation Model [97], the Health Belief Model [98], the Theory of Planned Behavior [99], the Transtheoretical Model of Health Behavior Change (TTM) [90], and the Precautionary Adoption Process Model [100].

Those health protection models suggest that knowledge about the risk is only one of the health behavior determinants, other determinants, explained in Table 12.3 below, being attitudes, perceived behavioral control, subjective norm, descriptive norms, moral norms, self-efficacy, risk

Table 12.2 Examples of acceptable radiation risks in relation to risk perception

Descriptive example of an acceptable radiation risk—a hypothetical scenario	Selected characteristics of risk	Influence on risk (un) acceptability	Explanatory scale
A catastrophic potential of a nuclear accident made the risk more threatening since low-probability high-consequence radiation risks are usually perceived as more threatening than more probable risks with low or medium consequences.	Catastrophic potential	Decreases risk acceptability	Catastrophic—chronic
Medical personnel is wearing assigned personal radiation dosimeters during a procedure using ionizing radiation, which gives a feeling of control and increases the acceptability of radiation exposure.	Personal control	Increases risk acceptability	Controllable—not controllable
A phosphate factory is recognized as a trustworthy organization since they communicate openly about the risks of naturally occurring radioactive material as a side product.	Institutional control	Depends upon confidence in institutional performance	Trust, confidence in the institution
Population density around nuclear installation is low thus controlled releases of radioactivity from a nuclear installation in an environment is acceptable.	Number of exposed	Decreases risk acceptability	Local—global
Workers get employed at a nuclear installation on a voluntarist basis thus they accept workers' exposure to ionizing radiation.	Voluntariness	Increases risk acceptability	Voluntary—involuntary
A patient receives a low dose of ionizing radiation during X-ray which makes it acceptable.	Mortality	Decreases risk acceptability	Fatal—not fatal
Visitors learned about radiation and technology used by researchers during an open-door day at a nuclear research institute. New insights and knowledge influenced their acceptability of potential radiation risks.	Knowledge	Increases risk acceptability	New technology—established technology
Living in a home with high radon concentration for many years (more generations) made residents accept radon risk and not performing radon test or necessary remediation of a house	Familiarity	Increases risk acceptability	Familiar—not familiar
A traffic accident with transport of radionuclides for a hospital in a citizen's region is not as dreadful as a nuclear accident in another continent is.	Dread/fear	Decreases risk acceptability	Fear—no fear
High natural background of radiation is for many people acceptable because it is natural due to the geological characteristics of a region.	Artificiality of risk source	Amplifies attention to risk Often decreases risk acceptability	Human—natural
During an environmental remediation process, residents had a feeling of fairness since they could co-decide on how, where, and to which level should be environment remediated. Thus, they accepted radioactive residues in a dedicated part of their administrative community.	Fairness	Increases quest for social and political responses	Fair—unfair
Receiving compensation for radioactive waste disposal made the project acceptable.	Benefit	Increase risk acceptability	Benefit to self-vs. unclear or inequitable
Intake of stable iodine as an effective countermeasure for reducing the risk of thyroid cancer in an eventual release of radioactive iodine following a nuclear accident, especially for children, made the pre-distribution of the iodine tablets to residents and un uptake of a tablet if necessary, an acceptable option.	Effect on children	Decrease risk acceptability	Children specifically at risk

perception, protective efficiency of an action, threat, and trust among others. Table 12.3 presents potential health protection determinants, descriptive explanations, and a reference to selected studies that have been tested in the radiation protection field.

In particular, the Theory of Planned Behavior [124] proved that the higher the intent, the higher the probability an individual will engage in the action they intend. This theory has been for instance applied in research on attitudes and behavior related to new nuclear research installations [120]. In this study, authors found that attitudes towards participation and moral norms are the strongest determinants for the studied behavior—in this case, participation intention. Other determinants were time constraints, attitude towards nuclear energy, subjective and descriptive norms, and level of specific radiation-related knowledge. The Extended Parallel Process Model (EPPM) focuses on two constructs which mediate an individual's level of fear and proposes an individual will engage in behavior change when they have a combination of (a) fear the health threat will happen to them (susceptibility) and (b) perception they are able to address/deal with the risk [108]. The Transtheoretical Model of Health Behavior Change which has been applied among others also to behavior related to radon exposure [125], postulates that individuals move through six stages of change: pre-contemplation, contemplation, preparation, action, maintenance, and termination. The model has two major components: change and decisional balance, where neither

Table 12.3 Determinants of health and radiation protection behavior tested in radiation risk studies

Potential determinants of health and radiation behavior	Descriptive explanation	Selected studies from radiation protection field
Anticipatory emotion—worry	The anticipatory emotion—worry is an emotion where a person experiences increased levels of anxiety by thinking about an event or situation in the future.	McGlone et al. [101], Witte et al. [102]
Anticipatory emotion—severity	Anticipatory emotion—severity refers to people's beliefs about how serious are the negative consequences of a hazard. In the radon exposure situations, the threat involves cancer, which is severe.	Mazur and Hall [103], Dragojevic et al. [104]
Conditional/perceived susceptibility	Perceived susceptibility is the subjective belief that a person may acquire a disease or enter a dire state due to a particular behavior.	D'Antoni et al. [105], Weinstein et al. [106], Niemeyer and Keller [107]
Coping of efficacy appraisal: response efficacy	Coping appraisal is needed to adopt or maintain a health protection behavior and is essential for overcoming fears and mental blocks. Coping appraisal consists of three dements: response efficacy/response costs/self-efficacy. Only if the individual is convinced that a behavior leads to the desired outcome will she or he be more likely to intend to perform the behavior.	Weinstein et al. [108, 109], Witte et al. [110], Dragojevic et al. [104]
Coping or efficacy appraisal—self efficacy	Self-efficacy refers to the belief in one's own competence to perform a behavior even in the face of barriers or in other words, the individual in carrying out the recommended coping response.	Hahn et al. [111], Larsson [112], Rhodes et al. [113]
Perceived costs	The "Perceived costs" captures the person's perceptions of the disadvantages of, or barriers to, undertaking the behavior.	Hampson et al. [114], Sheeran [115]
Anticipated emotions/ regret	Anticipated emotions are a component of the immediate consequences of the decision; they are emotions that are expected to occur when outcomes are experienced. The most extensively researched anticipated emotions regret, guilt, and shame.	Hampson et al. [114], Sheeran [115]
Perceived informed choice	Informed choice means that people under radon risk make decisions that are consistent with their goals and values	Weinstein and Man [116, 117]
Subjective norms	Subjective norms refer to the belief that an important person or group of people will approve and support and particular behavior, for instance protection against radon	Clifford et al. [118], Park et al. [119]
Descriptive norms	Descriptive norms refer to what most people in a group think, feel, or do. Descriptive norms are a reflection on "What is typical or normal … what most people do", including "evidence as to what will likely be effective and adaptive action.	
Moral norms	Moral norms are internalised, unconditional and emotional internalised and enforced through self-generated emotions such as guilt.	Turcanu et al. [120]
Knowledge/awareness	Increasing radiation (specific) knowledge and awareness is often set as a primary objective of risk communication efforts.	Perko et al. [84, 121]
Trust	Trust concept includes different dimensions for instance fairness, unbiasedness, perceived competence, objectivity, consistency, commitment, caring, and predictability, social trust, general trust and transparency.	Perko and Martell [122], Perko et al. [123]

knowledge nor risk perception is not identified as the main health protection change determinants [126]. Similarly, the message design theories, such as the Extended Parallel Processing Model (EPPM) which has been used as the theoretical framework for formative and summative analysis of radon communication campaigns, indicate the importance of threat and efficacy [110].

12.6.4 Risk Communication

Responsible risk communication requires a legitimate procedure, an ethically justified risk message, and concern for and valuation of the effects of the message and procedure. This way, it is stressed, that risk communication should not only be effective but also ethical, which requires taking moral values into consideration. During radiation risk communication moral values are at stake, which means that decisions have to be made in a democratic way, after serious debate about values and not merely about numbers [127].

> *Risk communication was in previous century seen as a form of a technical communication and education whereby the public should be informed about risk estimates. Later on, risk communication was seen as a marketing practice with the aim to persuade people to adopt a certain message. In nowadays societies (sic), risk communication is seen as a socio-centric communication based on public participation with which the gaps between stakeholders can be bridged. The procedure should be legitimate (requires legitimate procedure for discussing the moral values and emotions associated with risks), it should be ethically justified (ethical deliberation about the values and emotions involved in different messages) and the effects should be adequately addressed.* [128, p. 8–9].

Radiation risk communication has several aims: (a) to warn people in case of radiation danger, (b) to the enlightenment of people to be able to understand risks and become "risk-literate," (c) to prevent panic and outrage, (d) to empower stakeholders to make informed decisions related to radiation risks, (e) to establish two-way communication and joint problem solving including conflict resolution, and (f) to build trust between different stakeholders.

Bauder and colleagues (2021) guide communication practitioners towards radiation risk communication which is strategic (e.g., based on formats and methods that have been proven to reach its preconceived objectives), evidence-based (e.g., based on the qualitative and quantitative empirical data, surveys, experiments), and theory-based (e.g., drawing from empirically supported theories of health behavior, behavior, and information processing) [129].

For instance, information processing theories applied in radiation risk communication [130] show that efficient communication about radiation risks requires thorough insight into the factors that influence people's attentiveness, recall of risk-related information, level of agreement with the communicated message, and behavior change or more generally speaking: how people process risk-related information and turned it in a behavior.

The information processing models are seen as applicable for each individual, regardless of the societal or cultural bias [131–139] however countries may differ in beliefs, cultural values, past social and risk experiences, the saliency of particular aspects of a policy issue, the socioeconomic profile and trust in regulatory agencies. In general, people process information using two different modes: (1) heuristic and (2) systematic mode [140]. Heuristic processing is characterized by low effort and reliance on existing knowledge and simple cues for instance trust. Systematic processing on the other hand is characterized by greater effort and the desire to evaluate information formally [141].

12.6.5 Advice on How to Communicate with the Public About Your Radiobiological Study

Radiobiologists may be challenged by public communication due to the following reasons [122]: there is no single audience for scientific information; the complexity of scientific methods and information, and the ways in which science progresses; the ways in which people process such information; in the radiobiology, the societal implications of science are controversial, for instance, Linear Dose Response Model; there is substantial disagreement about the findings within the scientific community, for instance, related to low doses; the complex, dynamic, and competitive communication media environment, with evolving social media and pace of information flow; and because the results of research can be insufficient, ambiguous or uncertain, and scientific conclusions can change over time as new findings emerge.

Science Media Centre (2012) developed practical guidance to be used by scientists during their public and mass media communication. For a complete and original guide, look at https://www.sciencemediacentre.org/wp-content/uploads/2012/09/10-best-practice-guidelines-for-science-and-health-reporting.pdf.

Some of the central points are summarized here:

- Headlines should not mislead the reader about a story's contents and quotation marks should not be used to dress up overstatement.
- During your communication related to health risks, include the absolute risk whenever it is available in the press release or the research paper (e.g., if "low dose exposure increases the cancer risk" state the outright risk of that cancer, with and without particular exposure).
- Especially on a story with public health implications, try to present a new finding in the context of other evidence (e.g., does it reinforce or conflict with previous studies?). If it attracts serious scientific concerns, they should not be ignored.
- When reporting a link between two things, it is recommended to indicate whether or not there is evidence that one causes the other.
- Specify the size and nature of the study (e.g., who/what were the subjects, how long did it last, what was tested or was it an observation?). Provided there is enough space and time, it could be of interest to mention also the major limitations.
- State where the research has been published or presented or reported (e.g., conference, journal article, survey, etc.). Ideally, the article should include a web link or enough information for readers to look it up.
- Give a sense of the stage of the research (e.g., new dosimeter, clean-up stage, cells in a laboratory, or trials in humans), and a realistic time frame for any new technology.
- If there is enough space, quote both the researchers themselves and external sources with appropriate expertise. Be wary of scientists and press releases over-claiming for studies.
- Distinguish between findings and interpretation or extrapolation; do not suggest health advice if none has been offered.

12.7 Exercises

12.7.1 Ethics

1. The most difficult thing in finding trust in decision-making on nuclear today might be in the way we deal with moral pluralism. What is moral pluralism? Simply the idea that if we all know the same thing, opinions on what to do can still be different, and this is because our opinions do not only rely on knowledge but also on ethical values. As an example choosing for retrievability or non-retrievability of underground stored nuclear waste is making a choice deal-

ing with moral pluralism: science can describe the options, but not help us to make a choice. Some would say we should dispose and seal the waste so that future generations do not need to bother about it anymore, while others would argue that we should give them the possibility to intervene or do something better with the waste. Imagine yourself being a moderator in this discussion: what are the values and interests at stake here, and how would you moderate this discussion towards a consensus, also taking into account that an important stakeholder (the future generations) cannot participate in the discussion?

2. Studies have shown that the public is more averse to relatively low radiation exposures from nuclear power than to higher doses from medical exposures. Is this irrational?
3. What other ethically relevant factors impact perceptions of radiation risks?

12.7.2 Law

1. Which is the main underlying principle of nuclear law and how does this translate to the concept of optimization of protection? Can you give an example of two planned exposure situations?
2. Do you think the exposure to cosmic rays is a planned exposure situation or an existing exposure? Could it be both in the context of air travel? Is radiological protection different in either situation?
3. What attributes should a regulatory body have and what are some of its main tasks?
4. Nuclear liability is different from general tortious liability. Give an example and explain the reason.

12.7.3 Legal Imputation

1. Taking into consideration the legal structure of your country, please elaborate on the potential legal developments of the following situations:
   (a) A worker is damaged (burned) by an over-exposure to radiation and decides the damage is to be attributed to the exposure and imputed on his/her employer;
   (b) A large group of conscripts is subjected to a collective medical screening using old X-ray equipment when joining the army. About a decade later, those still meeting in social encounters discover that a large number among them are suffering from unusual cancers for their young age and decide to impute the army;
   (c) A family is living near a nuclear power plant that appears to function as designed. There have been no reports of any anomalous events, incidents, or anomalous measured values. One of their children incurs thyroid cancer. The parents have contacted a lawyer.

Disclaimer

- At the time of the preparation of this book, Russia invaded Ukraine.
- The Ukraine War will have repercussions on the existing international paradigm governing protection, safety, security, and safeguards of endeavors involving radiation exposure.
- It may take years to answer the questions raised by the present crisis.
- The authors believe however that the ethical, social, and epistemological considerations presented below are still applicable. The legal and logistical considerations may change in the future in such a way that the relevant sections in this chapter will no longer be applicable.

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