Radioprotection 2017, 52(1), 21–28

DOI: 10.1051/radiopro/2017006

Available online at:
www.radioprotection.org

ARTICLE

What's next in *Radioprotection*?

M. Bourguignon[1,2,*], P. Bérard[3], J.M. Bertho[1], J. Farah[4], C. Mercat[5] and Radioprotection Editorial Board

[1] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France.
[2] UVSQ – Université Paris-Saclay, Montigny le Bretonneux, France.
[3] CEA, Fontenay-aux-Roses, France.
[4] Hôpitaux Universitaires Paris-Sud, Le Kremlin Bicêtre, France.
[5] Areva BS, Site de Tricastin, 26700 Pierrelatte, France.

Received: 8 February 2017 / Accepted: 9 February 2017

Abstract – In recent years, *Radioprotection*, the journal of the French Radiation Protection Society (SFRP) has evolved to an international peer-reviewed journal. This evolution, together with a recent change in the editorial board of the journal, stimulated a reflexion on the aims and topics of interest for the journal. The starting point of this reflexion is an analysis by the editorial board of the current issues in the various fields of radiation protection and the associated challenges in corresponding research areas such as epidemiology, fundamental radiation biology, biological and physical dosimetry, radiation toxicology, ecotoxicology and environmental radiation protection. This article presents the results of this think tank action and paves the way for an evolution of the aims and scope of the journal *Radioprotection*.

Keywords: radioprotection / medical exposures / radon / radiobiology / radiosensitivity / radiosusceptibility / epidemiology / dosimetry

1 Introduction

Radioprotection, the international journal of the French Society for Radiation Protection (SFRP), has continuously improved over the last years. Its has grown into a successful peer-reviewed scientific journal dedicated to radiation protection, indexed in major bibliographic databases and having an increasing impact factor. Success and growth have brought significant benefits but also raise significant challenges. Recently, a new editorial board was named and acknowledged the clear mission from SFRP of aiming further for excellence.

In the analysis of the possible ways towards an even better journal it appears useful to us to identify and to set down in writing the main topics for research and discussions in radiological protection. A recent survey of lectureship has indicated that reviews and synthesis on hot topics are favored by the readers of *Radioprotection*. Thus it is the goal of this position paper to identify and propose some directions for future publications in *Radioprotection*.

We consider that the main topics of interest in the field of radiation protection and for readers of *Radioprotection* are those in which new investigations and results may challenge the approach and the management of radiological protection. In a context of scarce resources the funding allocated to radiological protection are limited somehow in proportion of the real risk of ionizing radiation in comparison with other risks. Consequently, it is important to focus research efforts on key issues in radiation protection. Indeed "*An approximate answer to the right questions is worth a great deal more than a precise answer to the wrong question* (John Tukey)".

Therefore this position paper intends to identify the key issues in radiological protection that can be considered as the journal top priorities. The intention is to encourage the exchange of pertinent research and ideas within the radiological protection community. Manuscripts on these hot topics are thus very welcome in *Radioprotection*, albeit not excluding manuscript in other fields of radioprotection.

2 Scientific rationale

In order to discriminate those key issues it is worth coming back to the origins of radiation protection and its evolution. Looking at its historical development, we can identify the following successive steps.

It started with the initial observations of health effects of ionizing radiations (IR), *i.e.*, skin burns and cancers. For skin burns and other so called major deterministic effects the responsibility of IR is clear. For stochastic effects (cancers), the establishment of a causal relationship is more difficult. Epidemiologic studies have been quite useful to establish solid

* Corresponding author: michel.bourguignon@irsn.fr

correlations between the frequency of cancers and the dose of IR in the dose range above 100 mGy. These correlations strongly suggest some responsibility of IR in the appearance of cancers. However the demonstration that IR are the direct cause of cancer occurrence in a given individual has not been made so far even for the high doses of IR: there is no clear unquestionable and reliable biological marker of a radio-induced cancer and no confirmation of an unequivocable and specific mechanism of cancer induction by IR.

However, future epidemiologic studies may be limited for two reasons: (1) for better evaluations million people epidemiologic cohorts are necessary to increase their statistical power and to reduced uncertainties, especially in the dose range below 100 mSv and (2) the registration of doses of IR is usually not of a sufficient quality since data are sometimes gathered retrospectively and often incomplete. However it is quite clear that epidemiology has been very powerful to increase the knowledge regarding the health effects of IR for a large range of doses, *i.e.*, above 100 mGy. They have paved the way for an effective management of radiation protection.

The three ICRP principles of radiological protection, *i.e.*, justification, optimisation and limitation, have been very efficient for a optimized management of exposures. As a consequence, human doses have decreased quite substantially to the level of very low doses. The exposure of workers using IR has clearly decreased along the years and is now in the order of or below 1 mSv per year in most countries: 96% of French workers are below 1 mSv per year (IRSN, 2016) although some medical workers may exceed the dose limit of 20 mSv. The dose limit for the public is below the variations of natural background. The dose limits of the system of radiological protection are quite low and are not foreseen to be changed in the near future.

Then what's next in radiation protection?

The key issues we have identify belong to the following categories:

- the main exposures to IR and especially those which can be decreased or optimized;
- the dosimetric issues either for biological or for physical dosimetry;
- the future of epidemiology;
- the radiation biology which benefits today of new fantastic tools of investigations at the molecular, cell and tissue levels;
- the environmental radiation protection and ecotoxicology;
- and finally the necessary evolution of the system of radiological protection.

3 The main sources of human exposure to ionizing radiation

Medical exposures and radon are two main causes of exposures of the general population (Fig. 1). Dealing with them is a priority not only because they are the most important and the most frequent exposures to IR but also because they can be controlled to some extent. This can also be the case for naturally occurring radionuclide material (NORM) in the industry. Exposure and potential exposures in case of accidents also need to be considered.

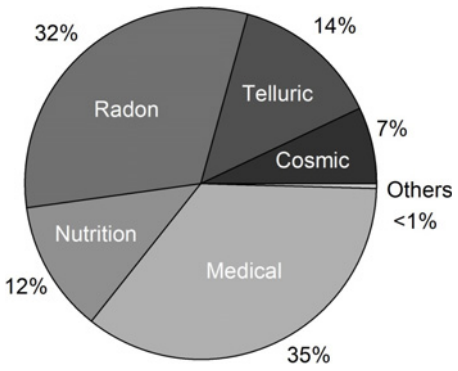

Fig. 1. Schematic representation of annual mean exposure of the French population for 2015. Source: IRSN report 2015-0001 available at www.irsn.fr.

Diagnostic medical exposure in patients accounts for one third of the mean annual human exposure. They are growing worldwide, *e.g.*, a factor two in the last ten years in France (IRSN, 2014) and a factor six between 1980 and 2006 in the USA (Herrman *et al.*, 2012). They will continue to grow because medical imaging is highly useful and beneficial for the diagnosis of diseases, the orientation of the therapeutic strategy, the follow-up of treatment and the treatment itself through interventional radiology or image guided procedures. On the other hand, the screening of diseases, such as mammography screening of breast cancer in women between 50 and 75 years of age, significantly contributes to the doses received by the population. Consequently the mean annual exposure due to medical diagnosis procedure will continue to increase in future years.

The variability of diagnostic medical exposures between the different countries is large (European Dose Datamed II Project Report, 2014) although CT brings the main contribution to the patient doses (>50%) in all of them (UNSCEAR, 2008). The medical effective doses reported in the literature (*e.g.*, 1.1 mSv in Europe and 3 mSv in the USA) are mean values obtained over the whole population. Thus they do not take in account the fact that a fraction of the population has any examination per year. Thus the annual medical-induced effective dose per exposed patient is quite high and largely variable according to the number and nature of medical examinations.

The principles of justification and optimization are the main tools to address the increase in medical exposures. Therefore their use must be enforced and their application extended, through the substitution of X-ray examinations by MRI or ultrasound, the revision of diagnostic reference levels, the increase use of clinical decision software (CDS), and continuous technical innovation by manufacturers to decrease CT dose for instance.

Another category of medical exposure is radiation therapy which is successfully used worldwide to treat about 50% of all cancers with a high success rate (about 80%). Since cancer risk increases with age and because the population is ageing, exposure to the healthy tissues surrounding the tumor by radiation therapy will increase. Complications and deterministic side effects of radiation therapy are not rare, affecting up to 10–15% of patients (Foray *et al.*, 2016) and secondary

cancers are observed in about 5% of treated patients. New radiotherapy equipments and techniques (conformational radiotherapy for instance) allow a better ballistics for dose delivery to the tumour, and consequently an escalation of dose and new fractionation paradigms. These advances due to innovation bring clever solutions to old problems but also raise many new issues, such as the large increase of normal tissues exposed to low doses of IR and the validity of the linear-quadratic model for the definition of new radiation therapy modalities (high doses in hypo fractionated protocols), and the increase risk of severe side effects in case of ballistic errors.

Radon exposures also account, on average, for one third of the total exposure of population but most of the population is exposed to low levels of radon. The absorbed dose to the lung is evaluated to 14.5 mGy/100 $Bq.m^{-3}$ and the equivalent dose to the lung to 290 mSv/100 $Bq.m^{-3}$. Epidemiology studies indicate that 10–15% of lung cancers are associated with radon exposure and that the effects of radon exposure and smoking (the main risk factor for lung cancer) are more than additive. Overall, only 2–4% of lung cancers can be attributed to radon only. On the other hand, radon exposure is higher in regions with a high background radiation exposure due to geological characteristics. In houses where ventilation is not optimal, this may result in a global pollution of indoor air. Therefore prevention of radon exposure should be considered together with that of smoking and other indoor pollutants. Research and evaluations on such a large topic are needed.

Accidental overexposures to industrial sources of high activity, *e.g.*, those used in nondestructive measurements in industrial radiology, are rare but quite harmful. Health consequences can be of two types: acute radiation syndrome and local skin burns. The treatment of these overexposures has made considerable progress in the last decade. Acute radiation syndromes benefit from cytokine treatment and lesser from marrow grafting and this therapeutic strategy was supported by an international consensus (Gorin *et al.*, 2006). Local skin burns are best treated by a combination of surgery and mesenchymal stem cell grafting (Lataillade *et al.*, 2007). In this context, the appropriate treatment and the follow-up of these injuries may improve through enhanced international cooperation. Two key points appear in this field. On the first hand, it is essential that the control and the safety of these industrial sources be increased in the future. The IAEA recommendation for a specific mark on these industrial sources is a first step but presents some risks and is not sufficient. The reflection on the safety of these industrial sources should continue. On the second hand, the comprehension of biological mechanisms underlying the success of radiation burn treatment by mesenchymal stem cells is essential. This could allow to develop and to extend this efficient treatment through international cooperation to other situations such as the treatment of serious side effects in radiation therapy.

Potential exposures in case of emergency situations and accidents also need to be considered since they may concern a large population over a large territory, involving low doses for a long period of time. A rather specific issue is related to the workers and rescuers who may receive high doses of ionizing radiation during the event and the long and difficult mitigation activities and management of waste for land recovery. Progress in this field will help rebuild the confidence of the public.

Research topics in emergency preparedness and response of relevance to radiation protection are:

- improve, harmonize and standardize modelling of the dispersion and environmental behaviour of radionuclides;
- improve knowledge regarding the environmental behavior of less well-known radionuclides including their chemical and physical speciation;
- improve and standardize techniques and procedures for radiation measurements and sampling and laboratory analyses of radionuclides;
- improve the knowledge on the health effects of chronic, long term exposures to both external and internal irradiation at low doses, including psychological effects;
- delineate the possible interactions between mixed exposures to IR and chemical pollutants on health effects;
- be prepared to health monitoring and post-accident epidemiologic studies: pre-existing health monitoring, involvement of the public, ...;
- anticipate issues related to living in contaminated areas: evacuation and coming back, psychological effects, ethics, remediation, ...;
- improve the communication between experts, the share of the knowledge with all the stakeholders and the communication about uncertainties to the public.

4 Dosimetry

Dosimetry is a critical tool in radiological protection since dose values are widely used for the management of exposures and are critical for the epidemiologic studies. Consequently doses must be determined with accuracy and recorded rigorously.

Doses resulting from external exposures are usually quite well evaluated. However there are numerous situations of exposures where dose assessment is more difficult, *e.g.*, protracted, repeated, fractionated exposures, interventional radiology and medical image guided exposures. In proton and heavy ion therapy and in some nuclear plants, stray neutron doses may also account for a substantial part of external exposures for some workplaces. Optimized detectors are necessary and a particular vigilance is required.

Conversely doses resulting from internal exposures are quite difficult to assess quantitatively with both accuracy and precision. Internal dose assessment relies on ICRP biokinetic models for inhaled and ingested radionuclides still being updated and on dosimetric models used to calculate doses to organs, tissues and at the microscopic level to cells or organelles. However, some of these biokinetic models are extrapolated on the basis of chemical and physical similarities between nuclides. Moreover, since these biokinetic models depend on the chemical speciation of the nuclide, they may not correctly describe the behaviour of some “targeted” radionuclides used in nuclear medicine (radioimmunotherapy using alpha emitters for instance) or exotic radionuclide speciations. Priority should be given to internal emitters encountered in occupational, accidental, natural and medical exposures including organically bound tritium, radon-222, plutonium-239, strontium-90, iodine-131, caesium-137, uranium radionuclides and radionuclides for internal radiotherapy (*e.g.*, radium-223, lutetium-177).

Thus the evaluation of the reliability of both kinetic and dosimetric models for internal dose assessment remains a priority.

Another field of interest is the biological dosimetry, *i.e.*, the quantitative assessment of exposure through biological parameters. The biological dosimetry is mainly based on DNA damage evaluation through detection of chromosomal aberration, γH2AX foci, comet assay, and so on. The sensitivity of these tests has improved in the past 10 years, allowing today to evaluate radiation exposure in the range of 0.1–0.5 Gy for exposure to gamma emitters. However, with the decreasing exposures to the workers and population and the concomitant increase in the need for a reliable measurement of exposure (especially for legal expertise), the biological dosimetry is pushed in a course to the highest possible sensitivity and the lowest uncertainty. This represents a great challenge for the field of biological dosimetry.

5 Epidemiology

As already indicated epidemiology is a pillar of radiological protection. Epidemiologic studies have provided highly significant data used for the elaboration of the current recommendations in radiological protection.

Up to the 1990s, A bomb survivors and radiotherapy patients were to some extend the main sources of information for the epidemiologic studies. These studies have demonstrated a dose–risk relationship between stochastic health effects and dose for moderate doses (above 100 mGy) delivered at high dose rate. They also showed that the risk of cancer after exposure to ionizing radiation alone at low dose (<100 mGy) and low dose rate (<5 mGy.h^{-1}) is small, since they have not been able to demonstrate a risk.

In the last decade, several epidemiologic studies provided results at low dose and low dose rates that were not available before: Mayak workers, Tetcha river residents, nuclear industry workers, patients with diagnostic procedures, Chernobyl liquidators, ... They have not been able to demonstrate a statistically significant risk at low dose up to now but extrapolation seems compatible with a linear no threshold relationship (LNT). Extension of these studies will provide additional results of great interest.

What can we expect more from epidemiology? And by what means?

According to statistical theory, epidemiologic studies increase their power with the size of the cohorts. The Australian study regarding medical CT exposures in million children (Mathews *et al.*, 2013) or the INWORKS studies combining 3 cohorts and more than 300 000 workers (Leuraud *et al.*, 2015; Laurier *et al.*, 2016) are examples of such a confirmation. Since it has proved useful this needs to be continued, *e.g.*, the European EPI-CT study which combines 8 cohorts and is still in progress (Bosch de Basea *et al.*, 2015). Nevertheless epidemiological studies have been somehow biased by their incomplete dose data, *e.g.*, the lack of medical exposures. For example, what are the medical doses received by the atomic bomb survivors during their decades of medical follow-up, or by the nuclear workers of the INWORKS studies during the medical follow-up of their long professional career? There are many reasons to suppose that these medical doses may be quite significant up to the point that they may modify the conclusions of the epidemiological studies. By how much still needs to be determined. Medical exposures certainly need to be recorded in the cohorts of Fukushima populations for the validity of future epidemiologic studies.

Epidemiological studies can also be biased when they do not take into account potentially significant exposures to the many other genetoxic compounds of occupational or private environment, *e.g.*, pesticides, alcohol, smoking and other chemicals polluting the atmosphere, etc. This may be the case in post-accidental situations in which the population is exposed to both ionizing radiation and chemical pollutants. Thus the risks of combined exposures need to be evaluated in the future. This is critical for the evaluation of low dose effects of IR since the lower they are the lower is their potential responsibility in the causation of cancer, a complex and delayed disease due to a poor combination of a number of DNA lesions (Weinberg, 2013).

Therefore there is a need to clarify the conclusions of the epidemiologic studies regarding the association of IR at low dose as a risk factor of cancer among others and the possible causation of the disease. Clarifications are needed and misinterpretations must be avoided!

Besides the increase in statistical power resulting from the size of the cohorts, epidemiology will gain strength by focusing on targeted cohorts selected on the basis of biological markers, *e.g.*, markers of an individual response to IR, possibly abnormal. With this respect, it will be of high interest to associate omics methods (genomics, proteomics, and other methods) with epidemiological studies. Such strategy might increase the analytical power of epidemiological studies. Furthermore these new cohorts may prove useful to clarify the relationship between health effect and dose at low dose: so far the linear relationship between health effects (cancer) and dose has been proved for doses above 100 mGy but radiation biology nowadays demonstrate a linear relationship between IR dose and DNA lesions down to 1 mGy (Rothkamm and Lobrich, 2003). Indeed a DNA lesion is not enough to yield a cancer but there are no cancers without DNA lesions and the accumulation of a minimum number of lesions (>10) is necessary. Thus can we fill the gap between health effects and DNA lesions? Can we scientifically expect to extend the LNT at lower levels at least for some subgroups of the population?

Finally some results from epidemiology suggest an association of exposures to IR with non-cancer effects such as cardiovascular diseases (Little *et al.*, 2012). Control of risk factors other than IR is needed. Future epidemiologic studies should provide confirmation in the next decade.

6 Radiation biology

Radiation biology has historically contributed to the progress in radioprotection. New tools of investigations at the molecular, cell and tissue levels have been recently developed. Since they bring new significant data that change the comprehension of the effects of IR radiation biology will gain a critical role in the future of radioprotection.

Thus extensive research must be carried out to address questions out of reach before and to answer many unknowns related to the large variety of exposures.

Great progress have been made in the domain of radiation biology as a part of fundamental biology since IR are also used as a disturbing agent. Significant results from the new tools of investigations can already be identified and more results can be expected:

- During the last decade, new techniques have appeared with a gain of sensitivity of detection of DNA lesions by a factor of 100, *e.g.*, γH2AX immunofluorescence of persistent DNA double strand breaks at the level of 1 mGy (Rothkamm and Lobrich, 2003). Many other immunofluorescent markers have been developed and permit dynamic cellular investigations: is the right protein at the right place at the right time (*e.g.*, ATM, Rad 51, MRE11, ...) (Granzotto *et al.*, 2016)? These new techniques allow nowadays a functional evaluation of DNA damage signaling and pathway responses (DDR) after IR exposure; the corresponding observations are quite significant. Results from omic investigations start to bring new insights on the effects of IR especially on the possible occurrence of a radiologic signature of cancers after high doses of radiotherapy (Behjati *et al.*, 2016).
- Global hyper-radiosensitivity to low doses of ionizing radiation (HRS phenomenon) corresponds to a quite significant increase in cell death at low doses (10–800 mGy with a peak at about 300 mGy) in comparison to higher doses (1 Gy) (Joiner *et al.*, 2001). HRS is linked to DDR mechanisms. The importance of HRS in current exposures still needs to be investigated.
- Regarding bystander effect the soluble compounds which carry the genetoxic and clastogenic effects need to be identified. As well, the occurrence and importance of bystander effect at the scale of the whole organism in the development of health effects need to be clarified.

An abnormal individual response to IR appears to be much more frequent than initially thought (up to 20% of the population) (Foray *et al.*, 2016). It raises public health issues which cannot be neglected. Individual response to IR appears to have 3 components: (1) individual radiosensitivity leads to severe deterministic effects related to increase cell deaths and lack of tissue homeostasis after exposures to high doses of ionizing radiation, *e.g.*, side effects and complications of radiation therapy although there is no mistake in the dose delivery; (2) individual radiosusceptibility is related to the survival of altered cells (a particular cancer proneness resulting from the exposure to ionizing radiation) and may be a signal of a more general cancer proneness. This second point highlights the issue of the combined risks of exposure to a series of genetoxic and clastogenic compounds even at low doses; and (3) individual radiodegeneration accounts for delayed non cancer effects such as cataract and cardiovascular effects. It seems also linked to an abnormal DDR.

The precise mechanisms of the individual response to IR start to be clarified, involve an abnormal DDR but more extensive research is needed.

Results obtained with these techniques confirm that lesions caused by ionizing radiation occur primarily in cellular DNA. The number of initial DNA lesions is linearly related to the dose: 40 DNA double strand break (DSB) lesions and hundreds of other DNA lesions are created on the average by 1 Gy of ionizing radiation, and may combine in complex lesions. The key point regarding the future of any altered cell is the capability to signal or not the presence of the DNA lesions and to repair them appropriately or not, even at low doses (Colin *et al.*, 2011). Thus signalization and repair of DNA lesions are keys of future radiobiology. They make the difference between individuals (Joubert *et al.*, 2008).

These new techniques of radiobiology should be used to clarify basic mechanisms and to possibly answer recurrent questions:

- Is there a difference in the response according to the dose and dose rate as described above or between external exposures and internal contaminations?
- What are the determinants of the absence or delay of signalization or repair of DNA lesions at low doses and their consequences?
- What is the influence of age at time of exposure and is there possible differential response related to gender?
- What is the importance of the non-targeted effects of radiation exposure?
- What is the role of the cellular environment and tissue reactions including metabolic pathways and inflammatory reactions? ...

Medical, radon and accidental exposures are very different in terms of dose and dose rate (Fig. 2) (Hubert, 2003). They may also significantly differ from the acute exposures (for example of the atomic bomb survivors) which have brought most of the knowledge regarding the effects of ionizing radiations. There are many other types of exposure that are of clinical relevance in medicine and for which there are no or little radiobiology results: the repetition of doses at short time intervals (*e.g.*, the second view of mammography), the use of contrast agents which yield a significant increase of absorbed dose, the repetition of examinations after which the total dose may exceed 100 mGy and the threshold of appearance of stochastic effects, the differences in response for different energies (*e.g.*, 30 kV of mammography *vs.* 120 kV of CT) and the biological responses related to new paradigms of radiotherapy. The effects of chronic and protracted exposures are not so well known either. Thus further research in radiation biology must be carried out to investigate all these questions which have no answer at the current time.

Although biological response and molecular mechanisms can be investigated in animals or cells derived from animals, research in human cells and tissues is necessary because human cells have somewhat a different level of complexity as compared to rodent models and some molecular mechanisms are specific to humans. Therefore studies on biological samples from human cell and tissue collections (*e.g.*, the United States Transuranium & Uranium Registries (USTUR) or the COPERNIC collection of fibroblasts from radiosensitive patients (Granzotto *et al.*, 2016), ...) should be encouraged. Multiple investigations on the same tissues will provide a better and more complete view of cellular mechanisms of response to IR.

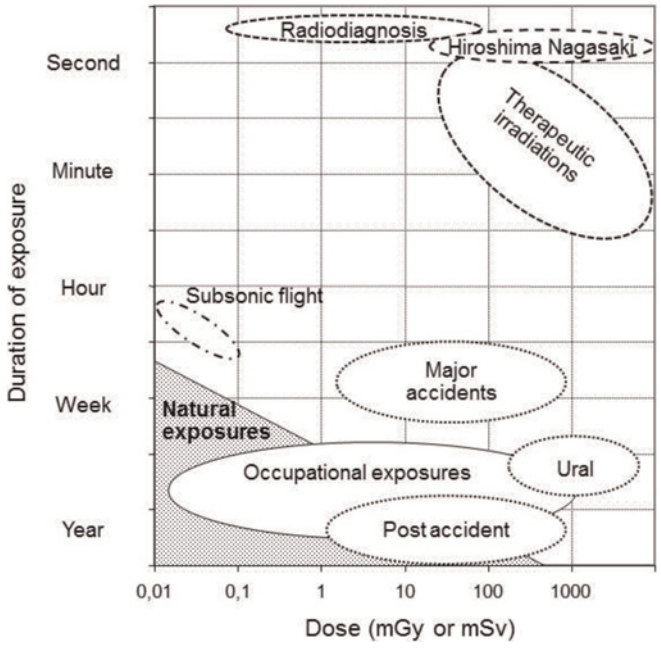

Fig. 2. Schematic representation of exposure situations according to the dose and the duration of exposure.

Finally radiation biology research in fauna and flora still need to be carried out as part of the radiological protection of the environment with the goal of understanding and characterizing similarities and differences in responses to exposures to IR.

7 Environmental radiation protection issues

The radiation protection of the environment developed considerably since the sixties, making available knowledge, robust methods and tools to assess the radiological risks for humans in their environment, and more recently for the environment itself. Many issues concerning external and internal exposures, biokinetic and dosimetric models have already been addressed in this article.

Initiated for about ten years, bringing together the assessment methods for the dosimetric impact and the risk assessment methods for chemical products has been interesting in terms of harmonization and optimization of the practices. Indeed, nuclear installations are also chemical plants and for number of them the sanitary effects of chemical exposure for the reference groups of the public prove finally to be higher than the dosimetric impact. Combined risk evaluation must continue and evolve to develop simplified tools integrating all the risk dimensions (protection of the public and protection of the ecosystems from both ionizing radiation and chemical substances) at the appropriate level of complexity in application of the principle of proportionality, *i.e.*, adequacy of the means to the sought-after goal. It is although of prime importance to confront results of risk evaluation to field observations on fauna, flora and biodiversity to check the accuracy of the models.

From an operational point of view, major industrial challenges concerning environmental radiation protection are coming from increase dismantling and industrial mutations which are necessary for number of nuclear sites. These kinds of operations must already cope with increasing difficulties in the management of the grounds excavated because of land constrained. The return at the natural state, *i.e.*, the cleansing of the totality of the added Becquerel, is a virtuous unavoidable dogma that is seldom achievable: continuity of the economic activities nearby a stopped installation, insoluble technical constraints to excavate such consequent volumes, lack of sufficient capacities of storage to accommodate these excavated grounds considered as nuclear wastes. The clarification of concepts regarding waste definition and management including clearance levels is needed. It is also necessary to progress in the research of cleansing criteria and in the identification of solutions operational for the operators which are acceptable by all the stakeholders.

Thus risk assessment, optimization of the authorized discharges, objective of cleansing of dismantling, post-accidental management of contaminated territories, ... are various themes of radiation protection of the environment to be opened for discussion within the radiation protection community and with the civil society much concerned with environmental print. The participative democracy makes essential to exchange of points of view, practices and experience feedbacks from all countries and to share priorities on environmental radiation protection issues.

8 The system of radiological protection

The system of radiological protection developed and updated by ICRP (2007) for more than eight decades has proved robust and operational.

The current review is an attempt to open the discussion in various fields of radiation protection. Such discussions may help to open ways for the future evolution of the system of radiological protection. We foresee four issues that may influence the future management of radioprotection and thus need to be further explored:

– *Risk evaluation*. The large majority of doses in humans are in the low dose range and even in the very low dose range. At this level of doses the risk is very low, at a level more than acceptable since epidemiology has not been able to demonstrate it up to now. For a given individual the effective dose cannot and must not be used for risk evaluation (ICRP, 2007). Since the main exposures, *i.e.*, medical and radon exposures, are targeted to specific organs, it seems logical to suppose that the risk is carried out by the organs exposed and not by the total body. Consequently it is desirable to develop risk evaluation based on doses to the organs exposed (absorbed and equivalent dose) and *ad hoc* risk models (UNSCEAR, 2012).
– *Human individual response to IR*. Patients with an abnormal response to IR should be identified to constitute large cohorts of persons to be studied by epidemiology since they present an increased risk after exposure to IR. Conversely cohorts of persons at risk of cancer should be investigated for their potential abnormal response to IR, *e.g.*, patients with high familial risk of breast cancer or non-smoking patients with lung cancers. On another hand patients who are likely to be

highly or repeatedly exposed to IR for medical reasons should be screened for a potential abnormal response to IR. Such screenings should be performed especially in children, in women, prior to radiotherapy or to repeated exposures such as radiology screening (mammography). Such studies may help to develop predictive assays which in turn should become part of personalized medicine.

– *Combined exposures*. How should we address the combined effects of low doses of genetoxic compounds, a situation of combined exposures corresponding to the everyday life for the majority of people? The respective effect of each of them is probably impossible to be determined. Thus is it reasonable to try to further determine the isolated risk of very low dose IR? Nevertheless, the possible occurrence of supra-additive effects with these combined exposures remains to be determined. However the radiological protection system appears as a strong precursor in the domain of risk prevention and the principles of justification, optimization and limitation of doses for all genotoxics could be reinforced and extended to other domains.
– *Education*. Due to lack of knowledge and understanding public and media perception of exposures to IR do not correspond to the real exposures and risks. Roughly public and media think mostly that natural exposures do not exist, medical exposures are good and exposures related to the nuclear industry are evil. Education of the public and media and health practitioners is necessary to give the radiological protection its appropriate place and not a sometimes overwhelming place on minor issues. Some pedagogy about LNT is necessary. A psychosocial approach of radiological protection needs to be developed. Personnel with broad knowledge, skills and competences in the field of radiation protection who are able to transmit the right scientific data must be maintained. Efforts should be made to confront estimated radiation risks to those of other agents. Stakeholders need to be deeply involved in education projects. The RP community shares the responsibility that public finances are appropriately used.

9 Conclusion

This review of the key issues in radiological protection has highlighted a number of needs to pave the way forward for *Radioprotection* in the future:

– need to deal with the most important and frequent exposures and to develop and validate new methods for reducing the corresponding doses, *e.g.*, reducing patient doses while improving image quality;
– need to carry out new radiobiology investigations with new available tools to answer many old and new questions which have not been addressed yet, *e.g.*, questions related to the large variety of doses and dose rates, or to the individual response to ionizing radiations ;
– need for more epidemiology studies based on quite large cohorts but also on new dedicated cohorts established on the basis of specific biomarkers;
– need for optimized dosimetry for both external and internal exposures;
– need to share practical experiences, especially in optimisation of environmental radiation protection during dismantling operations in order to improve the regulatory framework;
– need for new risk evaluation and to take into account combined risk to genetoxic compounds;
– need to keep competent personnel in the field of radiological protection and to educate both public and media on the critical issues.

Most of these needs have ethical components which have not been addressed in this review but should not be forgotten.

Your contributions in these numerous fields of research and expertise for the future of radiological protection are very welcome in *Radioprotection*!

References

Behjati S, *et al.* 2016. Mutational signatures of ionizing radiation in second malignancies. *Nat. Commun.* DOI: 10.1038/ncomms12605

Bosch de Basea M, *et al*. 2015. EPI-CT: design, challenges and epidemiological methods of an international study on cancer risk after paediatric and young adult CT. *J. Radiol. Prot.* 35(3): 611–628.

Colin C, *et al.* 2011. DNA double-strand breaks induced by mammographic screening procedures in human mammary epithelial cells. *Int. J. Radiat. Biol.* 87: 1103–1112.

European Dose Datamed II Project Report. 2014. European Commission, Radiation Protection no. 180, Part 1/2.

Foray N, *et al.* 2016. Individual response to ionizing radiation. *Mut. Res.* 770: 369–386.

Gorin NC, *et al.* 2006. Consensus conference on European preparedness for haematological and other medical management of mass radiation accidents. *Ann. Hematol.* 85: 671–679.

Granzotto A, *et al.* 2016. Influence of nucleoshuttling of the ATM protein in the healthy tissues response to radiation therapy: toward a molecular classification of human radiosensitivity. *Int. J. Radiat. Oncol. Biol. Phys.* 94(3): 450–460.

ICRP Publication 103. 2007. The 2007 recommendations of the International Commission on Radiological Protection. *Ann. ICRP* 37(2–4).

IRSN. 2014. Exposition de la population française aux rayonnements ionisants liée aux actes de diagnostic médical en 2012. Rapport IRSN-PRP-HOM no. 2014-6.

IRSN. 2016. La radioprotection des travailleurs. Exposition professionnelle aux rayonnements ionisants en France: bilan 2015. Rapport IRSN-PRP-HOM no. 2016-2.

Joiner MC, *et al.* 2001. Low-dose hypersensitivity: current status and possible mechanisms. *Int. J. Radiat. Oncol. Biol. Phys.* 49(2): 379–389.

Joubert A, *et al.* 2008. DNA double-strand break repair defects in syndromes associated with acute radiation response: at least two different assays to predict intrinsic radiosensitivity? *Int. J. Radiat. Biol.* 84(2): 107–125.

Herrman TL, *et al*. 2012. Best practices in digital radiography. American Society of Radiologic Technologists.

Hubert P. 2003. Pour un meilleur usage du risque attribuable en santé environnementale. *Environ. Risques Santé* 2(5): 266–278.

Lataillade JJ, *et al.* 2007. New approach to radiation burn treatment by dosimetry-guided surgery combined with autologous mesenchymal stem cell therapy. *Regen. Med.* 2(5): 785–794.

Laurier D, *et al.* 2016. The International Nuclear Workers Study (Inworks): a collaborative epidemiological study to improve knowledge about health effects of protracted low-dose exposure. *Radiat. Prot. Dosim.* 1–5. DOI: 10.1093/rpd/ncw314.

Leuraud K, *et al.* 2015. Ionising radiation and risk of death from leukaemia and lymphoma in radiation-monitored workers (INWORKS): an international cohort study. *Lancet Haematol.* 2: e276–e281.

Little MP, *et al.* 2012. Systematic review and meta-analysis of circulatory disease from exposure to low-level ionizing radiation and estimates of potential population mortality risks. *Environ. Health Perspect.* 120: 1503–1511.

Mathews JD, *et al.* 2013. Cancer risk in 680 000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ* 346: f2360.

Rothkamm K, Lobrich M. 2003. Evidence of a lack of DNA double-strand break repair in human cells exposed to very-low X-ray doses. *PNAS* 100(9): 5057–5062.

UNSCEAR. 2008. Estimates of worldwide average exposures (Vol. 1, Annex B), p. 404.

UNSCEAR. 2012. Attributing health effects to ionizing radiation exposure and inferring risks (Annex A).

Weinberg RA. 2013. The biology of cancer. New York, USA: Garland Science.

Cite this article as: Bourguignon M, Bérard P, Bertho JM, Farah J, Mercat C. 2017. What's next in *Radioprotection*? *Radioprotection* 52(1): 21–28.