

Initiatives of Low-Dose Research Co-ordination

Summary Report of a Joint
Workshop Organised by the
Nuclear Energy Agency
in Co-operation with the Electric
Power Research Institute

**NUCLEAR ENERGY AGENCY
COMMITTEE ON RADIOLOGICAL PROTECTION AND PUBLIC HEALTH**

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The objective of the Committee on Radiological Protection and Public Health (CRPPH) is to assist NEA member countries in the implementation and enhancement of the system of radiological protection. This objective will be met by identifying and effectively addressing those conceptual, scientific, policy, regulatory, operational and societal issues that either favourably or adversely affect the system of radiological protection, thereby promoting national and international good practices and identifying potential weaknesses and vulnerabilities.

To accomplish this, the Committee will contribute to the adoption and the maintenance of high standards of protection for the public, workers and the environment in all activities involving the use of ionising radiations, and particularly, but not limited to the field of nuclear energy.

In this context, the Committee on Radiological Protection and Public Health (CRPPH) shall:

- Provide a forum for the exchange of information and the transfer of experience between national radiological protection authorities on policies, regulatory issues and approaches, and their implementation in the context of realistic radiation exposure conditions, and as appropriate, the risks and regulatory arrangements for other common hazards.
- Seek international understanding and guidance, in support of national authorities, on questions of common concern regarding the interpretation and implementation of the ICRP recommendations and international standards in various fields of application of radiological protection, to contribute to the development of co-ordinated approaches among member countries, and to support the development of new international standards.
- Advance concepts and policies which make the system of radiological protection clear, transparent and adaptable to the broader social dimensions of decision making in complex situations, and further facilitate effective engagement with relevant stakeholders, including their involvement in decision making as appropriate.
- Promote international collaboration on specific radiological protection and radiation-related public health topics of interest to the NEA member countries in the framework of the NEA Strategic Plan.
- Keep under review, contribute to the advancement of, and identify needs for the state of the art in the field of radiological protection at the social-scientific, natural-scientific and technical levels, and promote the preparation of authoritative advice and reference documents, for use by national authorities, policy makers and practitioners, on emerging policy, regulatory and operational issues, and in those areas where international consensus on radiological protection concepts, regulatory issues and practices is sought.
- Help ensure the management of radiological protection knowledge and experience between generations of radiological protection experts.
- Actively interact with the International Commission on Radiological Protection (ICRP) to help link national policy and regulatory needs to the development of international recommendations.

In the fulfilment of its mandate, the CRPPH will work in close co-operation with other NEA Committees as appropriate, particularly the Committee on Nuclear Regulatory Activities (CNRA), the Radioactive Waste Management Committee (RWMC), and the Nuclear Law Committee (NLC), as well as with NEA divisions, and competent bodies within relevant OECD directorates and other international organisations active in the field.

Foreword

This joint workshop on low-dose research co-ordination was co-organised by the Nuclear Energy Agency (NEA) High-Level Group on Low-Dose Research (HLG-LDR) and the Electric Power Research Institute (EPRI) with its International Dose Effect Alliance (IDEA) network. The event was the culmination of ongoing collaboration between both organisations, fostered through a series of workshops and webinars focused on low-dose research.

The HLG-LDR aims to enhance radiological protection policy, regulation and implementation by improving the effectiveness and efficiency of research through global co-ordination of current and future low-dose research projects.

The health effects of low-dose radiation and their biological mechanisms in humans and non-human species are not yet fully understood. While cancer remains the most studied disease linked to ionising radiation, there is increasing evidence that low-dose (rate) radiation exposure may also be associated with non-cancer health outcomes, such as cardiovascular diseases, neurological disorders, immune dysfunction and cataracts. Questions also persist on potential transgenerational effects.

Advancements in research methods and technology have made it possible to expand the understanding of these radiation-related health effects. This progress underscores the importance and feasibility of improving our comprehension of the health risks associated with low-dose radiation exposure. The workshop convened 140 experts from 29 countries to discuss and share knowledge in the field of low-dose research with the following objectives:

- To share the latest research findings on low-dose radiation health outcomes and biological mechanisms in humans and non-human species, as well as new research methods and approaches.
- To identify and develop mechanisms for expediting outreach to the radiological protection community, highlighting the importance of co-ordination in low-dose research.
- To strengthen the development of educational and training resources for the next generation of researchers and radiological protection professionals.
- To create initiatives that bring together researchers and regulators, thereby amplifying the impact of key research findings and facilitating the transition of scientific research results into real-world applications.

This summary report captures the key findings and discussions of the workshop, with the objective of providing a valuable resource for the radiological protection community. It underscores the need for reinforced collaboration and co-ordination in low-dose research. By fostering knowledge sharing, this report aims to enhance understanding of the status of low-dose radiation health effects research and potential ways forward, serving as a meaningful tool to drive future research, bridge the gap between scientific discovery and practical/regulatory application, and support informed policy and regulatory decisions in radiological protection.

The summaries of the sessions in the different chapters are based on abstracts submitted by the speakers before the workshop as well as summaries of their presentations given in the room. The statements made are summaries of the presentations made by the experts and do not represent the official position of the Electric Power Research Institute or the Nuclear Energy Agency.

This report was approved by the Committee on Radiological Protection and Public Health (CRPPH) on 4 April 2025.

Acknowledgements

The Nuclear Energy Agency (NEA) expresses its appreciation to the Electric Power Research Institute (EPRI) for the collaboration in putting together this key workshop on low-dose research.

Appreciation is also directed towards the members of the Workshop Programme Committee for their substantial involvement and contributions to the overall success of the NEA-EPRI Joint Workshop on Initiatives of Low-Dose Research Co-Ordination. In particular, the NEA recognises the efforts of the programme committee members:

Dominique Laurier, Chair of the NEA High-Level Group on Low-Dose Research

Borja Bravo, Principal Technical Leader, EPRI

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The workshop also owes its success to the valued contributions of the guest speakers, presenters and panellists, all of whom generously shared their time, knowledge and experience with the workshop participants.

Both the workshop and the summary report were co-ordinated by the NEA Division of Radiological Protection and Human Aspects of Nuclear Safety (RP-HANS) under the oversight of Nobuhiro Muroya, Deputy Director-General for Management and Planning, and Nina Cromnier, Head of Division, with the support of Jacqueline Garnier-Laplace and George Vardoulakis, Deputy Heads of Division, Jan-Hendrik Kruse and Kerim Jaber, Junior Radiological Protection Specialists, as well as a cross-cutting team of NEA staff from divisions across the Agency.

Table of contents

List of abbreviations and acronyms.....	8
Glossary of key terms.....	10
Executive summary	11
1. Synthesis of recent research findings and their potential impact on radiological protection and public health	14
1.1 Effects of low-dose exposure.....	14
1.2 Low-dose exposure and diseases of the circulatory system effects	17
1.3 Overview of research progress in understanding transgenerational effects of low-dose (rate) exposure on living organisms	18
1.4 Results from childhood CT scan studies.....	19
1.5 Results of epidemiological studies on workers.....	20
1.6 Overview of the Fukushima Health Management Survey	20
1.7 US DOE Russian Health Studies Program	22
1.8 Biological effects of tritium exposure.....	23
1.9 Key takeaways and observations	23
2. Approaches and tools to improve research strategy	25
Part 1: Adverse outcome pathways (AOPs) and modelling approaches.....	25
2.1. Activities of the HLG-LDR Rad/Chem AOP Joint Topical Group	25
2.2. Human-mouse comparison of the multistage nature of radiation carcinogenesis in a mathematical model.....	27
Part 2: Innovative epidemiological approaches	27
2.3. High-throughput genome science: Towards the strategic goals of the Radiation Effects Research Foundation.....	27
2.4. Molecular epidemiology provides new insights into cancer risk after low-dose radiation exposure: Thyroid cancer after the Chernobyl nuclear power plant accident.....	28
Part 3: Existing databases, tissue archives, infrastructures	29
2.5. The NEA Global Register of Low-Dose Research Projects	29
2.6. Outcomes of the PIANOFORTE infrastructure workshop	29
3. Addressing weaknesses in low-dose research co-ordination and governance.....	31
Part 1: Experiences from co-ordinated project managers	31
3.1. PIANOFORTE – The European Partnership.....	31
3.2. Applied research strategy for health risk mitigation in Department of Energy operations.....	32
3.3. Fukushima Institute for Research, Education and Innovation in Japan.....	32
Part 2: Challenges and successes identified by the existing co-ordination networks	33
3.4. MELODI.....	33
3.5. ALLIANCE	34
3.6. COHERE	35
3.7. PLANET.....	36
3.8 Key takeaways and observations	37
3.9 Views of research funders and international organisations involved in science-based policies: A roundtable discussion.....	37

4. Global perspectives on education and training for radiological protection	40
4.1. Competence building in radiological protection to guarantee continuity and innovation	40
4.2. Perspectives from the HERCA Working Group on Education and Training	41
4.3. The ICRP Vancouver Call for Action and Mentorship Programme	41
4.4. Nuclear Energy Agency education initiatives.....	42
4.5. Key takeaways and observations	43
5. Structuring an open dialogue on low-dose research within the radiological protection community and beyond.....	44
5.1. Efforts of the HLG-LDR topical group on communication.....	44
5.2. The role of NEA schools in enhancing understanding of low-dose radiation issues.....	45
5.3. The art of communicating low-dose risk in a regulatory setting	45
5.4. EPA's perspective on radiation risk for Superfund sites	46
5.5. Enhancing understanding and communication in low-dose radiation research: A roundtable discussion	47
6. Workshop key takeaways	49
List of references	50
Annex A: Workshop agenda	54

List of tables

Table 1.1 Outline of the Fukushima Health Management Survey	21
Table 4.1 Nuclear Energy Agency Global Forum areas of work	42

List of abbreviations and acronyms

AI	Artificial intelligence
AOP	Adverse outcome pathways
ARAR	Applicable or Relevant and Appropriate Requirements
ASN	French Nuclear Safety Authority
BNEN	Belgian Nuclear higher Education Network
CANUWS	Canadian Uranium Workers Study
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (United States)
CHC	Comprehensive Health Check
CNRA	Committee on Nuclear Regulatory Activities (NEA)
CNSC	Canadian Nuclear Safety Commission
COHERE	Canadian Organisation on Health Effects from Radiation Exposure
CRPPH	Committee on Radiological Protection and Public Health (NEA)
CSN	Consejo de Seguridad Nuclear (Spanish Nuclear Safety Council)
CT	Computed tomography
DCS	Diseases of the circulatory system
DOE	Department of Energy (United States)
DSBs	DNA double-strand breaks
E&T	Education and training
EGPC	Expert Group on Public Communication of Nuclear Regulatory Organisations (NEA)
EHSS-13	The Office of Domestic and International Health Studies
EJP	European Joint Programme
EPA	Environmental Protection Agency
EPRI	The Electric Power Research Institute
ESCA	Emerging Science in Chemical Risk Assessment
ETC	Electron transport chain
EU BSS	Euratom Basic Safety Standards
FAIR	Findable, accessible, interoperable, reusable
FDNPS	Fukushima Daiichi Nuclear Power Station
F-REI	Fukushima Institute for Research, Education and Innovation
HERCA	Heads of the European Radiological Protection Competent Authorities
HLG-LDR	High-Level Group on Low-Dose Research (NEA)
ICRP	International Commission on Radiological Protection
IDEA	International Dose Effect Alliance
INFN	National Institute for Nuclear Physics (Italy)

IR	Ionising radiation
IRPS	International Radiological Protection School (NEA)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety [ASNR since January 2025])
KE	Key events
KER	Key event relationships
LDR	Low-dose research
LET	Linear energy transfer
MELODI	Multidisciplinary European Low Dose Initiative
MIE	Molecular initiating event
MPS	Million Person Study
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NEA	Nuclear Energy Agency
NEST	Nuclear Education, Skills and Technology
NGOs	Non-governmental organisations
OECD	Organisation for Economic Co-operation and Development
PIANOFORTE	European Partnership for Radiological Protection Research
PLANET	Planning and Action Network for Low Dose Radiation Research
PRG	Preliminary Remediation Goals
PTC	Papillary thyroid carcinomas
RAD/CHEM	Joint Radiation and Chemical Topical Group
RCTC	Nuclear Risk Communication Training Course
RERF	The Radiation Effects Research Foundation
RHSP	US DOE Russian Health Studies Program (discontinued in 2022)
RP	Radiological protection
RPE	Radiation protection expert
RPO	Radiation protection officer
SMR	Small modular reactor
SRA	Strategic Research Agenda
SSM	Swedish Radiation Safety Authority
TUE	Thyroid ultrasound examination
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US EPA	United States Environmental Protection Agency
USTUR	United States Transuranium and Uranium Registries
WHO	World Health Organization

Glossary of key terms

Adverse outcome pathways (AOPs)

A theoretical framework to understand how a harmful substance affects a living organism. It starts with the initial interaction of the substance with the organism at the molecular level, known as the molecular initiating event (MIE). This event triggers a series of steps, called key events (KEs), which are connected through key event relationships (KERs). These steps eventually lead to a harmful effect on the organism, known as the adverse outcome (NEA, n.d.).

Ionising radiation (IR)

Refers to radiation that has sufficient energy to remove an electron from an atom, a process known as ionisation. In living tissue, this effect can potentially lead to changes in DNA, which may result in cell mutation, including the development of cancer, or cell death (Arpansa, n.d.).

Low-dose radiation

Refers to exposure to ionising radiation at levels below 100 millisieverts (mSv) in total or at a rate below 0.1 millisieverts per minute (mSv/min) (NEA, 2021a).

Omics

Refers to molecular methods for measuring all of a certain molecular species in a cell (e.g. genomics, transcriptomics, proteomics and metabolomics) (NCRP, 2020).

Stakeholder

Any individual or group who has relevant information, experience or concerns to add to the decision-making process, or has other interests in the decision-making process, who may thus seek to participate and to interact with other stakeholders. Includes the concerned public, businesses, economic actors, non-governmental and civil society organisations, local, regional and national authorities, nuclear regulators, and others.

Executive summary

On 25-26 June 2024, a workshop on low-dose research co-ordination was held at the Nuclear Energy Agency (NEA) offices in Boulogne-Billancourt, France, jointly organised by the NEA High-Level Group on Low-Dose Research (HLG-LDR) and the Electric Power Research Institute's (EPRI) International Dose Effect Alliance (IDEA). This event brought together 140 experts from 29 countries, including representatives from NGOs and international organisations, both in person and online. The workshop, featuring contributions from about 50 international experts, facilitated comprehensive discussions across the spectrum of global low-dose research initiatives, emphasising the priority and relevance of their objectives.

The sessions at the workshop covered the following topics, which form the basis of the chapters in this summary report:

1. Synthesis of recent research findings and their potential impact on radiological protection and public health.
2. Approaches/tools to improve research strategy.
3. Addressing weaknesses in low-dose research co-ordination and governance.
4. Global perspectives on education and training for radiological protection.
5. Structuring an open dialogue on low-dose research within the radiological protection community and beyond.
6. Workshop key takeaways.

NEA Director-General William D. Magwood, IV emphasised the critical importance of low-dose radiation, which has been the subject of debate and discussion for decades. He noted that the nuclear sector is entering a new era and that with respect to low-dose radiation, the public's perception should guide research and policy. It is imperative to conduct research that acknowledges and responds to public concerns, driving decisive action.

The workshop chairs, Dominique Laurier (Institute for Radiological Protection and Nuclear Safety [IRSN] and chair of the HLG-LDR) and Borja Bravo (Electric Power Research Institute), recalled that low-dose radiation encompasses doses of ionising radiation below 100 mGy and are important due to their prevalence in everyday exposure. Fully understanding the effects of exposure to these doses is crucial for radiological protection policies and assessing risks associated with low-dose radiation. Despite remaining uncertainties in the low-dose range, current knowledge indicates that the risk is low at very low doses, a fact that must be effectively communicated.

The workshop highlighted pivotal advancements and emerging challenges in LDR and radiological protection (RP), with a strong focus on the implications for public health policies. Experts from around the world presented recent findings, showing a continuously improving understanding of risks associated with exposure to ionising radiation (IR), including the role of DNA damage in cancer development and the possible effects on tumour angiogenesis. Furthermore, research findings on cardiovascular and hereditary impacts of IR exposure were presented and discussed. It was acknowledged that medical imaging, particularly computed tomography (CT) scans, today significantly contributes to the public's annual exposure. In this context, the necessity for optimisation of exposure

through judicious use of medical imaging, especially in paediatric medicine, was highlighted.

The summaries of the sessions in the different chapters are based on abstracts submitted by the speakers before the workshop as well as summaries of their presentations given in the room. The statements made are summaries of the presentations made by the experts and do not represent the official position of the EPRI or the NEA. The speaker presentations are available to download for free on the event webpage: www.oecd-nea.org/jcms/pl_89517.

The workshop also explored the integration of adverse outcome pathways (AOPs) and modelling approaches, originally developed for chemical toxicology, into radiation research.¹ This integration is seen as a promising avenue to enhance the mechanistic understanding of the health impacts from IR, particularly at low doses. The establishment of a joint radiation and chemical (Rad/Chem) topical group within the NEA HLG-LDR aims to advance the use of AOPs in risk assessments and promote broader integration into environmental and public health strategies.

From an epidemiological standpoint, ongoing research such as that conducted by the Japanese Radiation Effects Research Foundation (RERF) on atomic bomb survivors, continues to provide important data. These studies help delineate the genetic alterations associated with radiation-induced cancers and other adverse health outcomes.

The challenges and successes of existing co-ordination networks in LDR were also discussed. While these networks have facilitated significant advancements by fostering collaboration and setting strategic research agendas, they face challenges such as securing adequate funding and achieving consensus on IR effects on biota and ecosystems.

Research funders and international organisations highlighted the need for robust mechanisms to handle the increasing volume of research data and literature. The emphasis was on ensuring a sustainable pipeline of skilled professionals through enhanced training and education initiatives. This is critical for maintaining the momentum in LDR and ensuring its integration into science-based policies.

The NEA HLG-LDR, established by the NEA Committee on Radiological Protection and Public Health (CRPPH) in 2019, has made significant strides in creating forums for debate and discussion to advance low-dose research. A key development has been the creation of a Global Register of Low-Dose Research Projects (www.oecd-nea.org/ldr), which is accessible to all stakeholders to foster collaboration and knowledge sharing.

Principal Team Lead at EPRI, Darcy Campbell, underscored the necessity of sharing feedback and knowledge internationally, further highlighting the IDEA initiative that was established to fill the international community's need for a collaborative forum, leveraging global resources.² Given that research on the effects of ionising radiation occurs in many countries, there is enormous potential for knowledge sharing.

In addition to the Global Register of Low-Dose Research Projects, the HLG-LDR has developed an AOP framework to facilitate collaboration and co-ordination between the chemical and radiation fields, promoting effective uptake of the AOP framework in low-

¹ For more details on the work of the OECD on AOPs, consult www.oecd.org/en/topics/sub-issues/testing-of-chemicals/adverse-outcome-pathways.html.

² Material from all former IDEA workshops is publicly available on www.epri.com/search#q=idea%20workshop&t=research&sort=relevancy.

dose research. A Rad/Chem AOP Joint Topical Group has been established to advance co-ordination of LDR using this approach (Chauhan et al., 2022).

Global perspectives on education and training in radiological protection emphasised the consequences of underinvestment in this area in many countries over the last decade. Initiatives like the ICRP "Vancouver Call for Action"³ and NEA projects like Plan 2035⁴ or the International Radiological Protection School⁵ aim to build a diverse, inclusive and gender-balanced workforce in RP.

The workshop culminated in a consensus on the need for more effective communication and public engagement strategies to demystify IR health impacts and enhance public trust. This involves not only improving risk communication but also ensuring that such efforts are continuous and not just reactive to emergencies. Overall, the participants underscored the critical need for a multidisciplinary approach to understanding and mitigating the risks of IR, fostering international collaboration, and engaging other stakeholders and the public in meaningful ways to address these common challenges.

³ See more on the Vancouver Call for Action at www.icrp.org/page.asp?id=647.

⁴ NEA project to address the global need to have a highly trained, diverse and gender balanced workforce in place by 2035. For more on this consult www.oecd-neo.org/jcms/pl_92775.

⁵ For more on the IRPS consult www.oecd-neo.org/jcms/pl_27505.

1. Synthesis of recent research findings and their potential impact on radiological protection and public health

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This chapter delves into recent research findings on the health effects of low-dose radiation exposure, highlighting its implications for cancer risk and other health concerns. It explores the role of AOPs as a tool to better understand the mechanisms underlying radiation outcomes. Beyond cancer, the chapter examines the increased understanding of non-cancer health outcomes such as cataracts, the sensitivity of the brain to radiation, and diseases of the circulatory system. Additionally, it covers the findings from childhood CT scan studies and the comprehensive Fukushima Health Management Survey. Lastly, the chapter discusses radiation health studies, with a focus on tritium exposure, providing a thorough overview of the diverse and complex effects of radiation on human health.

1.1 Effects of low-dose exposure

There is an increasing body of knowledge on cancer risks following low-dose radiation exposures, particularly from epidemiological studies of radiation workers and patients undergoing medical diagnostics. While these studies provide evidence of risk at lower doses, they primarily rely on mathematical or statistical models and lack a biological rationale for risk extrapolation. Mechanistic understanding is essential to bridge this gap, as epidemiology, though advanced in quantifying cancer risk, cannot establish causation or identify risk at the lowest doses and dose rates.

Recent literature has expanded significantly on the mechanisms of carcinogenesis following low-dose radiation exposure. In 2021, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) published Annex C, detailing biological

mechanisms relevant for cancer risk inference at low doses.⁶ This report, supported by extensive research literature identified through PubMed, underscores the importance of integrating mechanistic understanding with epidemiological findings.⁷

There is robust evidence that DNA damage induction following ionising radiation exposure and its subsequent cellular processing plays a critical role in cancer development. Variants of genes involved in chromatin remodelling also affect cancer risk, highlighting the complexity of radiation-induced carcinogenesis. Emerging research suggests that moderate dose levels of radiation may stimulate tumour angiogenesis, suggesting an influence of radiation exposures in later stages of carcinogenesis, thereby adding to the complexity of the mechanistic risk landscape.

AOP approaches have attracted interest for their potential to consolidate and integrate mechanistic understanding into risk assessment frameworks. AOPs systematically evaluate mechanistic evidence, identifying “molecular initiating events” and “key events” leading to adverse outcomes, such as cancer. Originally developed for chemical risk assessments, AOPs are now being applied to radiation outcomes.

Incorporating biological details, such as the two-pathway model of colon carcinogenesis developed by (Kaiser et al., 2014), enhances our understanding of the intricate processes underlying radiation-induced cancer. With the expanding evidence base and tools like AOPs, further progress in understanding the mechanisms of radiation-induced carcinogenesis at low doses is anticipated.

Additionally, radiation exposure poses other health risks beyond cancer. At low or moderate doses, cataracts are a significant concern due to the high radiosensitivity of the lens. Cataracts involve a clouding of the normally transparent lens and are the primary cause of visual impairment globally. Cataracts are curable, typically through a day surgery. In 2011, the International Commission on Radiological Protection (ICRP) classified cataracts as deterministic effects with a dose threshold of 0.5 Gy (ICRP, 2012), assuming that dose rate does not affect cataract risks and that minor opacities progress into vision-impairing cataracts. However, recent studies have reported elevated risks of lens opacities below 0.1 Gy in protractedly exposed US radiologic technologists⁸ and residents of high natural background radiation areas in China.⁹ The increased risk for cataract surgery has been primarily observed in Japanese atomic bomb survivors, leaving the progressive nature of radiation cataracts uncertain.

Epidemiological studies with extended follow-up tend to support a linear dose-response relationship rather than a threshold model for lens opacities. While the ICRP assumes that dose rate does not alter cataract risks, some experimental evidence suggests that lower dose rates might actually increase the risk of cataracts compared to higher dose rates.¹⁰ The mechanisms behind the high radiosensitivity of the lens are not fully understood but may

⁶ UNSCEAR publications can be consulted here www.unscear.org/unscear/publications/2020_2021_3.html.

⁷ PubMed can be used as a primary source to identify relevant papers, with a primary focus on those published between 2006 and 2020. However, these search terms should not be used exclusively: low-dose radiation, low dose-rate radiation, cancer, and mechanisms, can be accessed via <https://pubmed.ncbi.nlm.nih.gov/>.

⁸ See www.ncbi.nlm.nih.gov/pmc/articles/PMC7779357/.

⁹ For more on this consult the article by Su et al., <https://pmc.ncbi.nlm.nih.gov/articles/PMC7779357/>.

¹⁰ For more on this consult the article by Barnard et al. <https://pmc.ncbi.nlm.nih.gov/articles/PMC6639373/> and this article by Matsuya et al. <https://pmc.ncbi.nlm.nih.gov/articles/PMC1130169/>.

involve lens epithelial cell abnormalities and accelerated ageing. The high sensitivity of the lens to low linear energy transfer (LET) radiation may involve abnormal proliferation and differentiation.

In addition to cataracts, an increased risk of normal-tension glaucoma has recently been reported in atomic bomb survivors and Russian Mayak nuclear workers.¹¹ If confirmed, this finding has significant implications, as glaucoma is an incurable disease. Overall, the latest knowledge supports the ICRP assumption regarding the lack of dose protraction effects. However, the existence of a threshold for cataracts, the progressive nature of radiation-induced cataracts, and the potential risks of radiation-induced glaucoma warrant further research and discussion.

A long-held tenet appears to remain unchanged: the lens is among the most radiosensitive tissues in the eye and the body.

Beyond the eye, ionising radiation effects on the normal brain depend on multiple factors such as total dose, mode of irradiation (acute, chronic, fractionated), dose rate, exposed brain region, irradiated volume, and the age of the exposed individual. High radiation doses delivered to the brain for the treatment of primarily malignant or metastatic brain tumours are known to induce cognitive impairment and memory deficits, with severity correlating with the dose.¹² The developing brain is particularly sensitive to ionising radiation damage, suggesting that IR exposure during childhood leads to a higher risk for late neurocognitive sequelae.

From a public health perspective, the long-term consequences of low-dose radiation to the brain represent an increasing concern, mainly due to the growing number of medical diagnostic investigations involving radiation exposure. Although the number of such investigations tends to decrease in children, approximately 7% of total CT indications still involve children and young adults. Epidemiological studies on this matter are contradictory, but certain studies have shown impaired cognitive function in adulthood after moderate doses of ionising radiation exposure in childhood, such as the Swedish hemangioma cohort.¹³ These epidemiological observations were experimentally validated in murine studies with mice neonatally or perinatally irradiated with doses below 500 mGy. These results question the impact of dose rates on cognitive impairment.

The exact mechanisms responsible for cognitive defects are not yet fully elucidated, but damage to proliferating neuroprogenitors, inflammatory reactions, altered cellular signalling, and changes in the levels of various neurotransmitters have all been implicated in this process. Inflammation in the brain leads to the secretion of pro-inflammatory cytokines by damaged neurons and microglia activation. These processes contribute to radiation-induced cognitive impairment through neuroinflammation.

Severity of radiation-induced cognitive impairment varies, with acute effects such as fatigue, nausea, vomiting, headache and drowsiness appearing within hours to days and usually being reversible. Early delayed effects like attention deficits and short-term memory loss may also occur, typically reversible as well. However, severe and late effects can be irreversible, and the potential development of conditions such as Alzheimer's after long intervals from brain irradiation remains contested.

¹¹ For more on this consult the paper by Azizova et al <https://pmc.ncbi.nlm.nih.gov/articles/PMC8833586/>.

¹² For more on this consult Greene-Schloesser et al, 2012.

¹³ For more on this consult the publication at <https://pubmed.ncbi.nlm.nih.gov/32735015/>.

The risk factors for developing cognitive impairment include age, with individuals between 7 and 60 years being most sensitive, and higher fraction doses (above 2 Gy) leading to more significant brain damage. Cohorts suitable for studying these impairments include children exposed prenatally to irradiation, such as after the A-bomb in Japan, and cancer patients receiving radiotherapy.

Low-dose radiation effects on cognitive function have been studied, but available evidence is limited. Epidemiological observations indicate no significant effects on cognitive decline after exposure beyond 13 years of age, no effect of head CT at the age of 6-16 years on cognitive function in young people, and higher prevalence of cognitive and psychological deficits in Chernobyl clean-up workers exposed to doses above 100 mSv, particularly above 500 mSv. Higher rates of stress-related disorders were also observed.

Currently, the epidemiological evidence on low-dose irradiation-induced cognitive effects is limited or inadequate, highlighting the need for further studies to identify long-lasting and clinically relevant alterations. In utero exposure is a well-recognised deterministic effect, with significant reduction of the intelligence quotient per Gy while doses below 100 mGy are of no practical significance for cognitive deficits.

1.2 Low-dose exposure and diseases of the circulatory system effects

Historically, exposure to high doses of ionising radiation has been consistently linked to cardiovascular and cerebrovascular diseases, collectively known as diseases of the circulatory system (DCS). However, the causal relationship between low doses and dose rates and DCS remains debated. Past reports cited limited epidemiological evidence and a lack of biological mechanisms to support a causal link between DCS and doses below 1-2 Gy. Recent studies increasingly suggest an elevated risk of DCS at lower doses and dose rates than previously thought. Evidence for an increased risk of DCS following exposure to ionising radiation at low to moderate doses and dose rates has been observed in survivors of atomic bombings, individuals exposed following nuclear accidents, as well as occupationally exposed individuals and those receiving diagnostic exposures. Interestingly, analyses of selected dose regions below 500 mGy have suggested an inverse dose effect, with larger risks per unit dose for lower doses (Little MP, 2023). However, other new studies show no increased risk (Boice JC, 2022), and significant heterogeneities between studies make definitive risk assessment in the low-dose range difficult.

DCS represent several challenges for epidemiological studies, such as their complex natures, long latency periods and multiple risk factors. Therefore, strengthening the biological plausibility of epidemiological findings and elaborating data for biology-based modelling are critical future tasks. The biological mechanisms of radiation-induced DCS are still far from being fully understood. As part of developing AOP concepts, mechanistic information on radiation-induced processes in cardiovascular tissues has been evaluated and linked to pathological endpoints. A well-supported model has emerged, highlighting inflammatory processes, endothelial cell dysfunctions and changes in metabolism and extracellular matrix organisation as core processes leading to vascular remodelling, myocardial pathologies and fibrosis (Chauhan, 2024). Considered sources of information include animal models, cell culture studies, and analysis of human heart autopsies, with modern "omics" examining doses as low as 100 mGy and below.

In the context of radiological protection, DCS raise critical scientific questions on the shape of the dose-response curve, the potential existence of a threshold for adverse effects, and the impact of dose rate. There are ongoing international activities to address these questions, including two active working groups within the International Commission on

Radiological Protection, namely ICRP 123 and ICRP 119¹⁴, with the latter focusing on cardiovascular diseases. The United Nations Scientific Committee on the Effects of Atomic Radiation report for the seventieth session covers this topic.¹⁵

Environmental exposure studies indicate mostly linear increases in risk with no threshold and larger risks for longer lag times, with no elevated risks observed for regions with high background radiation or Fukushima. Occupational exposure studies have found dose-response relationships between cumulative external radiation dose and DCS mortality. In medical exposure, linear dose responses have been noted in breast cancer patients for various clinical DCS-related endpoints, with the risk decreasing with older age and more recent treatment (Chauhan et al., 2021).

An example for a key pathway involved in vascular function is nitric oxide signalling. This pathway is regulated by radiation in a dose rate- and fractionation-dependent manner, even at doses down to 500 mGy (Sadhukhan, 2020). New models, including 2D and 3D models of cardiac tissues and living myocardial slices, are being developed to monitor radiation effects over longer periods and measure influences on the beat rate (Smit, 2021). These models are crucial for advancing our understanding of related DCS and addressing knowledge gaps in the low-dose region.

In summary, recent evidence shows that doses of irradiation much lower than previously considered can cause adverse effects on the cardiovascular system.¹⁶ Complex radiation responses of the cardiovascular system and key steps in pathology have been identified. New models are ready to be used, but significant knowledge gaps remain, particularly in the low-dose and dose-rate area. The impact of modifiable and non-modifiable risk factors, such as lifestyle and genetics, may influence individual risks. Bioassays for radiation effects on the cardiovascular system and dose-response data for modelling are essential for future research. Implementing new models that are ready to be used is vital, given the significant knowledge gaps in low-dose research.

1.3 Overview of research progress in understanding transgenerational effects of low-dose (rate) exposure on living organisms

The hereditary impacts of ionising radiation across multiple generations continue to be a significant concern for radiological protection, with controversies stemming from inconsistent results in epidemiological studies. Although there is some evidence of increased congenital abnormalities in populations exposed to occupational ionising radiation, conclusive proof of hereditary health effects from preconceptional ionising radiation exposure remains elusive. The ICRP Task Group 121 is working to evaluate existing data to enhance radiological protection guidelines, stressing the importance of standardised measurements and the sharing of primary data.

Researching hereditary effects is inherently complex, particularly due to the difficulties in reconstructing dose exposure over the lifetime of an individual. Additionally, understanding how mutations and epigenetic changes, such as DNA methylation and miRNA expression, segregate over generations and potentially cause harm remains

¹⁴ See list of ICRP Task Groups: www.icrp.org/page.asp?id=404.

¹⁵ UNSCEAR report can be consulted here <https://documents.un.org/doc/undoc/gen/v23/057/73/pdf/v2305773.pdf>.

¹⁶ Recent findings suggest that lower doses than previously considered may have cardiovascular effects, for more on this consult www.ncbi.nlm.nih.gov/pmc/articles/PMC5144922/.

challenging. Maternal effects and stress responses further complicate the study of heritability by affecting offspring health.

Insights into hereditary effects can be drawn from non-human biota exposed to radionuclides, such as those in Fukushima and Chernobyl, which show transgenerational genetic and epigenetic alterations. Eco-epidemiological studies on these biotas indicate significant genetic changes passed down through generations due to radiation exposure. Moreover, animal experiments in radiobiology and ecotoxicology have unveiled mechanisms of heritability, including the roles of epigenetics, maternal effects, stress responses, and adaptation/selection. These studies suggest that IR exposure can induce genomic instability, leading to a series of changes in subsequent generations.¹⁷

The insights gained from these studies are crucial for comprehending the full range of radiation effects and for formulating effective radiological protection strategies.

There is a need for a thorough review and standardised data collection to improve radiological protection guidelines, with an emphasis on the complexities in researching heritable effects, including reconstructing lifetime dose exposure and understanding the segregation of mutations and epigenetic changes. By synthesising these insights, we can enhance our understanding of IR's hereditary effects and develop robust guidelines to protect future generations from the potential long-term impacts of radiation exposure.

1.4 Results from childhood CT scan studies

Medical ionising radiation exposure represents a significant portion of the annual radiation exposure of the general population, with CT scans contributing a large part due to their higher doses compared to conventional radiology. The use of CT scans has dramatically increased over the last 40 years, including in pediatric patients, who now account for about 10% of CT scans performed annually. Given the increased sensitivity of children to IR, numerous studies have focused on the risks associated with CT exposure in young patients.

The EPI-CT study, conducted across nine European countries, pooled data from around 1 million children and young adults, using anthropomorphic phantoms to account for uncertainties.¹⁸ The results indicated significant increased risks of brain cancer and haematological malignancies associated with CT scan doses much lower than 100 mGy. Sensitivity analyses confirmed the robustness of these findings, and potential methodological biases, including bias by indication, were examined and found not to impact the results significantly. These results are comparable, though slightly higher, than those reported in the Life Span Study.

In addition, a Korean study examined the risk of hematologic malignant neoplasms after childhood head CT scans.¹⁹ This population-based study utilised data from Korea's Health Insurance System, comparing 100 CT-exposed cases (including 66 leukaemias) with 808 non-exposed cases (including 537 leukaemias). The study aimed to rule out bias by indication in this population, confirming an increased incidence of hematologic malignancies associated with radiation exposure from head CTs in children and adolescents with minor head trauma.

¹⁷ This article discusses IR exposure in relation to inducing genomic instability, www.mdpi.com/2072-6694/9/7/91.

¹⁸ See <https://epi-ct.iarc.fr/>.

¹⁹ For more on this consult <https://link.springer.com/article/10.1007/s00330-023-10134-z#citeas>.

These studies highlight the importance of radiological protection rules in medical practice, emphasising the need for optimisation of delivered doses, justification of exams, and replacement with non-ionising radiation procedures when possible. The findings reinforce the necessity of adhering to these protective measures to mitigate the increased cancer risks associated with CT exposure in pediatric and young adult populations. Understanding these risks and protective measures is crucial not only for medical contexts but also for occupational settings.

1.5 Results of epidemiological studies on workers

The synthesis of recent epidemiological studies on the relationship between exposure and health effects among workers begins with the historical context of the Manhattan Project (1943-45) in the United States, which had parallel efforts in Canada, France (1945), the Soviet Union and the United Kingdom. This initiative expanded into a global enterprise involving various sectors, with an early focus on labour concerns and compensation issues.

In the 1960s, an epidemiological study was launched to investigate the association between radiological exposure and long-term diseases. By the late 1970s, facility-specific reports began to appear in the scientific literature, such as a study of workers in Tennessee. These reports found risk estimates that tended to be relatively or highly uncertain, with some showing evidence of positive associations with leukaemia, while others did not.

Two groups of investigators worked to address the issue of statistical instability, which was due to small sample sizes or low event numbers. Efforts in the United States led some of the initiatives to aggregate data.

An international effort to aggregate data, the International Agency for Research on Cancer's three-country study, focused on solid cancers, leukaemia, and ischemic heart disease.²⁰ The expected magnitude of association with radiological exposure was smaller than estimates from the Life Span Study.

Since the 1980s, there has been a significant increase in information regarding radiation-disease associations among workers. Many analyses now combine data across facilities and, in some cases, across nations. With larger sample sizes and increased numbers of events, there is now a greater focus on biases, transportability and the conditions necessary for identifying causal effects.

1.6 Overview of the Fukushima Health Management Survey






Fukushima Prefecture initiated the Fukushima Health Management Survey after the Fukushima Daiichi Nuclear Power Plant accident in 2011 and commissioned Fukushima Medical University to conduct the survey. The mission of the survey was to ascertain the external exposure doses of all 2.06 million Fukushima residents and the health status of Fukushima's people, aiming to prevent, promptly detect and properly treat medical conditions of all sorts, to maintain and improve participants' health into the future. None of the casualties of the Fukushima Daiichi accident were related to radiation, and there is a great difference in size and dose levels between Fukushima and Chernobyl.

The survey comprises the Basic Survey and four detailed surveys: the Thyroid Ultrasound Examination (TUE), Comprehensive Health Check (CHC), Mental Health and Lifestyle

²⁰ The study published by WHO can be accessed here <https://publications.iarc.fr/Book-And-Report-Series/Iarc-Technical-Publications/Combined-Analyses-Of-Cancer-Mortality-Among-Nuclear-Industry-Workers-In-Canada-The-United-Kingdom-And-The-United-States-Of-America-1995>.

Survey, and Pregnancy and Birth Survey. Approximately 2 million residents received the survey, including all residents aged 18 years or younger at the time of the disaster. The preliminary Basic Survey included approximately 2.06 million participants, and the detailed surveys included approximately 381 000 participants. The Basic Survey results showed that 99.8% of respondents (467 000, with a response rate of 27.7%) had estimated external doses of less than 5 mSv.²¹ The dose estimation results were considered "not being at a level where health effects can be confirmed with a statistical significance in light of the scientific knowledge obtained to date."

Table 1.1 Outline of the Fukushima Health Management Survey

Type	Participants	Number	Method of survey & response
Basic Survey	Residents of and visitors to Fukushima during the disaster	Approx. 2.06 million	 Self-report questionnaire to be submitted by post
Detailed Surveys	Preliminary Baseline Survey: All residents aged 18 or younger at the time of the disaster Full-Scale Surveys: In addition to those mentioned above, people who were born from April 2, 2011 to April 1, 2012	Approx. 368,000	 Thyroid examinations are performed at schools, medical facilities, and public facilities.
1. Thyroid Ultrasound Examination (TUE)		Approx. 381,000	
2. Comprehensive Health Check (CHC)	Residents of 13 municipalities designated as evacuation zones (Other municipalities are covered by the prefectural health check program)	Approx. 210,000	 Health checks are provided at medical facilities, municipal health check venues, etc.
3. Mental Health and Lifestyle Survey (MHLS)	Residents of 13 municipalities designated as evacuation zones	Approx. 210,000	 Self-report questionnaire to be submitted by post or online
4. Pregnancy and Birth Survey (PBS)	Main Survey: Those who received a Maternal and Child Handbook in Fukushima Those who give birth in Fukushima Follow-up Survey: Respondents to the Main Survey	12,000 - 16,000/year 5,000 - 7,000/year	 Self-report questionnaire to be submitted by post or online

Source: Yasumura, 2024.

The TUE has been an arbitrary examination for all residents aged 18 or younger at the time of the disaster, with 368 000 eligible participants. After a primary examination, confirmatory examinations are offered to individuals as needed. Participants are informed about the advantages and disadvantages of being examined before taking or not taking a thyroid examination. The TUE revealed 328 cases of suspected or actual thyroid cancer as of the 5th round (through 30 September 2023). The subcommittee for TUE evaluated the results as "unlikely to be an effect of radiation."

Eligible participants for the Comprehensive Health Check (CHC) and Mental Health and Lifestyle Survey are residents of 13 municipalities designated as evacuation zones, totalling approximately 210 000 people. The CHC results indicated no findings suggesting radiation effects, although adverse effects on mental and physical health were observed, especially among evacuees, who were at higher risk than non-evacuees. The CHC also showed that after the Great East Japan Earthquake, obesity has improved, but dyslipidaemia has

²¹ Source: 48th meeting of the Oversight Committee for the Fukushima Health Management Survey (20 July 2023).

persisted, and risk factors for circulatory diseases are increasing. General mental health measured by the K6 scale (for adults aged 16 years or older) indicated that 6.1% of people surveyed still need support 10 years after the disaster.²²

The Pregnancy and Birth Survey has been conducted every year after the accident for those who received a Maternal and Child Handbook in Fukushima and those who gave birth in Fukushima. The survey revealed that the rates of premature birth, low birth weight, and congenital anomalies were on par with the national average, indicating that the long-term effects of post-disaster low-dose radiation are considered to have no effect. Consequently, the survey was ended.

It is necessary to establish a new framework to understand the increasingly diverse needs of patients and the public over time. This framework should enhance understanding, streamline information dissemination and incorporate engaging public relations strategies. By doing so, it will be possible to ensure that radiological protection guidelines are understood by all parties and adhered to.

1.7 US DOE Russian Health Studies Program

The Office of Domestic and International Health Studies at the United States Department of Energy (DOE) has a significant history of supporting and managing research programmes on the health effects of low-dose radiation, such as the United States Transuranium and Uranium Registries (USTUR), the Million Person Study (MPS), the Japan Program, and the Russian Health Studies Program (RHSP). An update on the RHSP was provided during the workshop, which studied workers of the former Mayak nuclear weapon production site and residents in surrounding communities along the Techa River in the southern Urals of Russia. Initiated on 14 January 1994, under a bilateral agreement between the United States and Russia, the RHSP aimed to co-operatively study the health effects of ionising radiation. However, DOE funding to support Russian scientists was discontinued on 14 March 2022, leading to efforts to orderly close out the RHSP.

The RHSP's purpose was to study the risks associated with low-dose radiation. The close-out process involves completing data analysis, model development and publications, aiming to publish findings in a special issue of a peer-reviewed journal. An important aspect of this process is archiving and preserving 30 years of research for future researchers, ensuring the data remains accessible and cohesive.

A significant event in this process was the ICRP workshop entitled 30 Years of Scientific Achievements for International Radiological Protection, held on 24-25 May 2024, summarising the RHSP's scientific accomplishments²³. Over its duration, RHSP investigators published over 380 peer-reviewed publications, with findings frequently used by ICRP Committees and Task Groups and other national and international organisations.

The RHSP made major scientific achievements, particularly through the Mayak study, demonstrating the effects of internal alpha exposures on lung, liver and bone cancer rates. The studies of Mayak workers and Techa River populations revealed that radiation effects are well described by linear models with observed cancer and non-cancer effects. Solid cancer risks from chronic exposures in the RHSP are similar in scale to the acute exposures observed in the Life Span Study of atomic bomb survivors. Building on this understanding of radiation effects, recent research has also delved into other sources of exposure.

²² Source: The 48th Oversight Committee for the Fukushima Health Management Survey (20 July 2023).

²³ Link to event www.icrp.org/page.asp?id=656.

1.8 Biological effects of tritium exposure

A recent study investigated the potential human health risks associated with exposure to tritium (^3H), particularly following public concerns from events like the Fukushima Daiichi wastewater release.²⁴ The study aimed to address uncertainties regarding the comparative risks of external versus internal tritium exposures and to define the relative biological effectiveness of tritium β -radiation. Currently, the accepted RBE for low-energy β -radiations, including tritium, versus gamma-radiation is 1, but studies have shown varying RBEs from 0.4 to 3.5.

In this research, 1 500 female mice were exposed internally to tritium via tritiated drinking water with concentrations of 0, 150, 500, 1 200 and 3 000 MBq/L for 14 days. The calculated internal target doses ranged from 0 to 1 599 mGy, with dose rates from 210 mGy/h to 4.76 mGy/h. Following irradiation, the mice were monitored and terminally ill animals were euthanised. Tissue samples and observed abnormalities were analysed histopathologically, creating a database of survival and tumour profile data for each dose cohort. Results indicated a complex biological response at the lowest doses, with delayed tumour development and no significant changes in lifespan.

The study found that survival might be a better indicator of radiation-induced harm than cancer mortality. Tumour induction showed most tumours were not likely fatal, with liver tumours being the most common malignant type and ovarian tumours the most common benign type. Kaplan-Meier survival curves indicated increased early and late survival at 0.15 GBq/L compared to controls. These findings suggest that survival in tritium-irradiated mice could be explained by two competing effects, highlighting the need for further investigations to inform the low-dose radiation adverse outcomes pathway. Overall, the study underscores the complexity of biological responses to low-dose tritium radiation and the importance of survival as a metric for radiation-induced global impact

1.9 Key takeaways and observations

Participants noted several key points regarding the impacts of low-dose radiation and its effects on various health aspects.

Regarding cancer risk, it was highlighted that epidemiology is effective in assessing risks, but still lacks precision at very low doses.

Regarding the effects of radiation on the eye, it was noted that even minimal doses can show stress mechanisms, justifying the use of specific models for risk inference. The importance of combining these models with mathematical insight to enhance understanding was also emphasised. Additionally, the existence of a threshold depends on the type of ocular impact, suggesting a need to reconsider the classification between stochastic and tissue effects.

The cognitive effects of low-dose radiation were discussed, indicating that current evidence is limited and that there are challenges in classifying these effects, as they encompass a diverse range of diseases. There was a strong emphasis on the need for further studies to better understand these impacts.

²⁴ Based on results of published biokinetic study (Priest et al, 2017, Health Phys. 112 (5): DOI: 10.1097/HP.0000000000000637).

The usefulness of threshold classification in managing cancer risks was discussed, with growing evidence of the effects of low doses being noted. Additionally, the complexities involved in studying animals were highlighted, adding new dimensions to the research.

It was demonstrated that it is possible to reduce biases in big data studies, and the importance of long-term follow-up to progress in this area was stressed. The need for strong criteria to distinguish between high-quality and low-quality studies was also pointed out.

The discussion on results from CT scan studies also covered the observation of a noted decrease in risk over time with exposure, which might be linked to the population structure.

When considering subtle cognitive changes, it was suggested that comparing to previous exposure situations rather than a control population might be more relevant.

Questions were raised about the magnitude of radiation risks associated with medical imaging procedures, particularly CT scans, and their implications for patient health. The importance of quantifying these risks was stressed, highlighting that while CT scans are crucial, when necessary, unnecessary scans should be avoided due to potential cancer risks. It was emphasised that communication around these risks should be mindful of ensuring patients do not refuse essential medical procedures, and that healthcare professionals carefully consider the decision to order a CT scan by balancing the benefits and risks.

Workshop participants highlighted the necessity of engaging populations and explaining to them the connections between various factors and the overall health of the population. The link between the support that low-dose radiation research brings to radiological protection standards was emphasised, acting as a reminder that all data are useful. The Life Span Study showcased the difficulty in obtaining real-life data.

Participants noted that there are many variables to consider, including the type of data that should be collected. For instance, they questioned whether there are frameworks in place to follow up with people who gave birth during an accident, especially their offspring. They stressed the importance of following up with women who were pregnant during the Fukushima Daiichi accident.

The impact of medical exposure on the analysis of nuclear workers was discussed, noting that exposure levels have significantly increased since the 1990s, resulting in a doubling of the cumulative dose for these workers.

Regarding lung cancer screening, participants discussed whether it makes sense to try to calculate an excess risk for combined exposure to gamma and alpha radiation. Research has been done on combined exposure, with further studies set to take place.

2. Approaches and tools to improve research strategy

Part 1: Adverse outcome pathways (AOPs) and modelling approaches

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This chapter explores the application of the so-called AOPs in radiological protection, focusing on the efforts and activities of the HLG-LDR Rad/Chem AOP Joint Topical Group (www.oecd-nea.org/jcms/pl_89086). This section highlights the utility of AOPs in organising the current state of knowledge on the mechanistic understanding of radiation effects and improving risk assessment strategies. Additionally, it introduces AOP-helpFinder, an innovative search tool designed to facilitate the development of AOPs by efficiently gathering and prioritising relevant biological information from scientific literature. The chapter also delves into the human-mouse comparison of the multistage nature of radiation carcinogenesis, offering insights into quantitative risk prediction.

2.1. Activities of the HLG-LDR Rad/Chem AOP Joint Topical Group

In the field of chemical toxicology, a systematic framework has been developed for documenting and assessing key biological events within a causal chain, starting with a molecular initiating event (MIE) and progressing through a series of key events (KEs) that lead to an adverse outcome. This framework, known as AOPs, is managed by the Organisation for Economic Co-operation and Development (OECD) Emerging Science in Chemical Risk Assessment (ESCA) working party and provides a structured approach for identifying knowledge gaps and directing future research to support regulatory needs.

An AOP begins with an MIE, triggered by a stressor, linked to a sequence of KEs at various levels of biological organisation, ultimately leading to an AO at the individual or population level (OECD, 2018; Ankley et al., 2010). These events are interconnected by key event relationships that describe their causal links, enhancing the understanding of overall toxicity (Becker et al., 2015). AOPs are modular and stressor-agnostic, allowing them to be assembled into complex networks. This modularity helps evaluate and identify risks posed by various stressors on health and the environment, promoting interdisciplinary collaboration (Villeneuve et al., 2014).

Recently, this framework has attracted attention from the radiological protection and research sectors as a tool to enhance the mechanistic understanding of health impacts resulting from exposure to ionising radiation at low doses and dose rates. To fully utilise the potential of AOP methodologies in advancing risk assessment and management within radiological protection, shared experiences and collaboration between the chemical and radiation communities are necessary. Consequently, a Rad/Chem Joint Topical Group was established to promote the utilisation of AOPs in radiation research and encourage their broader integration into hazard and risk assessment practices (Chauhan, et al., 2022).

With diverse and global representation, this group serves as a platform for dialogue and collaborative initiatives aimed at supporting research and addressing regulatory challenges. It aims to establish active communication with the OECD AOP Developmental Programme to advance shared interests and provide recommendations for adapting the AOP framework to accommodate non-chemical stressors, such as radiation (e.g. AOP 272 [Sherman et al., n.d.]). By bridging the gap between chemical toxicology and radiological protection, the group seeks to enhance the mechanistic understanding of radiation effects and improve risk assessment. Additionally, it aims to foster collaboration and dialogue within the radiological protection community and beyond by establishing an open forum for discussing low-dose research (Chauhan, Hamada et al., 2022). Ultimately, the expectation is to contribute to the refinement of regulatory practices and the promotion of public health.

Understanding the effects of radiation on human and non-human biota and ecosystems is a complex challenge requiring insights into radiation's impact at multiple biological levels, including gene, cell, tissue, organ and organism. The AOP framework has emerged as a conceptual tool for organising and evaluating this knowledge for assessing radiation hazards in both human and non-human organisms (Burt et al., 2023; Chauhan et al., 2024). While its application in radiation studies is less extensive than in chemical research, significant progress has been made recently, with more than 15 AOPs developed for radiation, several of which focus on non-human organisms (Tollefsen et al., 2022).

Given the vast amount of existing knowledge, identifying relevant biological information to build AOPs is complex and time-consuming, especially when deciphering dispersed data in scientific literature. To facilitate this process, AOP-helpFinder was developed by Carvaillo et al. (2019), Jornod et al. (2022), and Jaylet et al. (2023). This innovative Python tool combines graph theory and text mining to automatically explore scientific abstracts from the PubMed database. It offers two search methods: one that identifies and extracts published associations between user-provided lists of stressors and key biological events, and another that extracts links between pairs of biological events. For each pair, a confidence score is assigned, helping users prioritise results and identify potential knowledge gaps.

AOP-helpFinder is freely available online at <https://aop-helpfinder.u-paris-sciences.fr> and represents a valuable resource for efficiently gathering and prioritising information from the literature at all levels of AOPs. The tool has been applied to develop AOPs initiated by ionising radiation, such as establishing an AOP for radiation-induced microcephaly, highlighting a lack of information on low-dose effects. Additionally, it has been employed in an integrative systems biology approach, providing supplementary information to developed AOPs. Currently, an AOP Network (AOPN) evaluating the synergy between radon and tobacco on lung cancer, based on data extracted by AOP-helpFinder, is under development.

The AOP framework offers numerous advantages, such as harmonising hazard characterisation approaches, identifying knowledge gaps and research priorities, and improving our mechanistic understanding of radiation-induced adverse effects. AOPs provide a structured method for linking molecular and cellular events to adverse outcomes, enhancing the robustness and transparency of hazard characterisation. Additionally, AOPs aid in transitioning from hazard to risk assessment for ionising radiation and multiple stressor effects by integrating qualitative and quantitative AOPs into the evaluation process. This integration enhances precision and relevance for risk assessment. Case studies illustrate how AOPs can be effectively used to improve understanding of radiation and multiple stressor hazards in environmental contexts (Sherman, et al., 2023; Kozbenko et al., 2022; Carrothers et al., 2024; Sleiman et al., 2024; Sandhu et al., 2024).

2.2. Human-mouse comparison of the multistage nature of radiation carcinogenesis in a mathematical model

Mouse models are essential for risk assessment of ionising radiation, but interspecies differences in dose response preclude direct application of experimental findings to humans. A mathematical approach was used to delineate the mechanism underlying the human-mouse difference in radiation-related cancer risk. Using a multistep carcinogenesis model, which assumes a mutagenic effect of radiation, previous data on cancer mortality in Japanese atomic bomb survivors and in lifespan mouse experiments were analysed. The model predicted that radiation exposure shifts the age-related increase in cancer risk forward in time, corresponding to the period in which the spontaneous mutation process generates the same mutational burden as that generated by exposure. This model fits both human and mouse data and suggested a linear dose response for the time shift, with the effect per dose decreasing with increasing age at exposure similarly in humans and mice (0.72- and 0.71-fold, respectively, for every tenth lifetime). The time shift per dose was significantly greater in humans (7.8 years per Gy) compared to mice (0.046 years per Gy) when exposed at approximately 35% of their lifetimes. This difference was largely explained by the two orders of magnitude difference in spontaneous somatic mutation rates between species, plus the species-independent radiation-induced mutation rate.

The findings suggest that humans have about 100 times lower mutation rate than mice, leading to a greater time shift per dose in humans. These results delineate the mechanism underlying the interspecies difference in radiation-associated cancer mortality and may enhance the use of experimental evidence for quantitative risk prediction in humans.

The integration of AOPs into radiological protection represents a significant advancement in understanding and assessing the health impacts of ionising radiation. The HLG-LDR Rad/Chem AOP Joint Topical Group exemplifies collaborative efforts to bridge the gap between chemical toxicology and radiation research. Tools like the AOP-helpFinder streamline the process of identifying key biological events, making the development of AOPs more efficient and comprehensive. The comparative study of the multistage nature of radiation carcinogenesis in humans and mice provides valuable insights into interspecies differences, enhancing the applicability of experimental findings for human risk assessment. These developments collectively enhance our capability to evaluate and manage the risks associated with radiation exposure.

Part 2: Innovative epidemiological approaches

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2.3. High-throughput genome science: Towards the strategic goals of the Radiation Effects Research Foundation

The Radiation Effects Research Foundation (RERF), supported by the governments of the United States and Japan, has studied the medical effects of radiation on atomic bomb survivors and their offspring since 1947. Thanks to the co-operation of those affected, RERF maintains five high-quality cohort studies that have been used to study radiation-related cancer and non-cancer morbidity and mortality. These studies are informative due to their large size, wide range of exposure levels, inclusion of all ages at exposure, and

long-standing, high-quality follow-up of disease outcomes. In addition to epidemiological data, clinical examinations and longitudinal serial collection of bio samples provide a unique opportunity to conduct integrated studies on genetic and epigenetic effects associated with health risks.

RERF's strategic plan emphasises integrated research programmes, leveraging expertise through collaboration with Japanese and international institutions to answer key questions in radiation science. Current studies include a whole genome analysis of exposed parents and their children (the "Trio Genome Study") to assess hereditary effects and an analysis of clonal haematopoiesis dynamics after radiation exposure. Foundational activities for building an ecosystem for integrated research include developing a bio sample research centre to centralise the collection, preparation and storage of bio samples, and a research resource centre to archive records of historical and scientific value, integrate data from various studies, and facilitate access for collaborative research.

2.4. Molecular epidemiology provides new insights into cancer risk after low-dose radiation exposure: Thyroid cancer after the Chernobyl nuclear power plant accident

Tumours that develop after radiation exposure exhibit increased frequencies of deletions, structural variants and fusion drivers. These characteristics, indicative of DNA double-strand breaks (DSBs), are not unique biomarkers for radiation-induced cancers since they can also result from other exogenous exposures and endogenous processes. To distinguish between radiation-induced and sporadic tumours, high-quality whole genome sequence data from fresh-frozen papillary thyroid carcinomas (PTCs) in radioactive iodine (¹³¹I)-exposed individuals post-Chernobyl accident were analysed (Yeager et al., 2021). The study focused on PTCs with common primary oncogenic drivers: fusions (N=140), primarily involving RET or other receptor tyrosine kinases, and BRAFV600E substitution (N=162).

For fusion drivers, the number of DNA DSBs and the extent of loss or gain at breakpoints were analysed. Among these, 66 were generated from 2 DNA DSBs with less than 20 base pairs of gain/loss at the breakpoint, 21 from 2 DNA DSBs with 20 or more base pairs of gain/loss at least one breakpoint, and 47 from multiple DNA DSBs, mostly with at least one breakpoint exhibiting 1 000 or more base pairs of loss. Through orthogonal analyses, it was demonstrated that only tumours with fusion drivers from 2 DNA DSBs with less than 20 base pairs of gain/loss at the breakpoint were consistent with radiation causation. Other tumours driven by fusions or BRAFV600E substitution showed no such associations.

Although a unique biomarker for radiation-induced tumours was not identified, this study provides valuable insights into radiation-related carcinogenic mechanisms and could assist in determining the probability of causation.

Part 3: Existing databases, tissue archives, infrastructures

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2.5. The NEA Global Register of Low-Dose Research Projects

Epidemiological and radiobiological studies on the health effects of low-dose ionising radiation are often lengthy and costly, with results taking years to publish. This delay hinders early and mid-stage dissemination, limiting opportunities for international collaboration and informed decision making by advisory, regulatory and funding bodies. Consequently, this can lead to suboptimal funding decisions and inefficient use of skills, resources and facilities.

To address these challenges, the HLG-LDR has developed the Global Register of Low-Dose Research Projects. The primary goal is to create a straightforward system for collecting and sharing key information on current and upcoming LDR projects. This initiative serves as a searchable database covering diverse disciplines such as epidemiology, radiobiology, dosimetry, ecotoxicology, social sciences and humanities.

Each entry in the LDR Register includes essential information for potential collaborators and stakeholders, such as opportunities for sample sharing. Additionally, in response to the growing interest in the Adverse Outcome Pathway concept within the research and regulatory communities, a dedicated field has been added to tag projects addressing AOP as one of their objectives.

The LDR Register is organised to benefit various communities by enhancing collaboration, resource sharing, and efficient dissemination of information. Its relevance extends to other databases and archives that collect information from radiobiological studies, aiming to engage all relevant communities and encourage active participation from institutions and individual research groups.

2.6. Outcomes of the PIANOFORTE infrastructure workshop

The European Partnership for Radiological protection Research (PIANOFORTE) unites 58 partners from 22 EU countries, the United Kingdom, and Norway to enhance the protection of the public, workers, patients, and the environment from environmental, occupational, and medical exposure to ionising radiation.²⁵ PIANOFORTE Work Package 5 (WP 5) focuses on developing and sustaining infrastructures that support EU radiological protection research. Key tasks include providing FAIR (Findable, Accessible, Interoperable, Reusable) access and training, promoting harmonisation of quality standards, and embedding the FAIR principles and open science in all activities.

In January 2024, WP 5 organised the first PIANOFORTE Infrastructures Workshop at the National Institute for Nuclear Physics (INFN) in Catania, Italy. The workshop aimed to gather insights from infrastructure partners on current best practices and requirements, identifying how WP 5 can support infrastructures within the PIANOFORTE partnership.

²⁵ For more on PIANOFORTE consult <https://pianoforte-partnership.eu/>.

The event featured presentations from selected infrastructures followed by focused working group sessions. These sessions addressed WP 5 areas of interest, including defining critical infrastructures, ensuring quality assurance, standardising and harmonising FAIR principles and practices, conducting intercomparisons, and providing training.

The workshop was highly successful, with contributions from infrastructures and interested parties both within and outside PIANOFORTE, including early career researchers. The reported experiences and needs are currently being compiled for publication in the open literature. Additionally, two calls are being prepared related to access and training for infrastructures.

WP 5 is making significant progress towards establishing a sustainable system for infrastructures and open science within EU radiological protection research. Contributions from all stakeholders in the wider community are encouraged, and participation in the planned follow-on workshop is welcomed.

3. Addressing weaknesses in low-dose research co-ordination and governance

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Part 1: Experiences from co-ordinated project managers

3.1. PIANOFORTE – The European Partnership

Building on the first European Joint Programme (EJP) between 2015 and 2020, PIANOFORTE follows a call by the European Commission in 2021 for a partnership among radiological protection entities. Currently it integrates over 80 research teams and includes representatives of the six European Research platforms, fostering a comprehensive pan-European scientific and technological foundation. The partnership targets three primary objectives: contributing to Europe's Beating Cancer Plan and SAMIRA plan, contributing to the EU Green Deal, and supporting the Sendai Framework for risk reduction and resilience.

PIANOFORTE's governance structure is based on three pillars: co-ordination to ensure effective resource and knowledge sharing, integration of various dimensions to enhance radiological protection, and fostering stakeholder dialogue to create added value from research. This governance is supported by four key tools: open calls, education and training activities, strengthening research infrastructures, and efforts for dissemination and communication of research.

The partnership emphasises reducing uncertainties in health risk estimates, particularly in medical applications, which are the largest artificial source of radiation exposure in Europe. It aims to contribute to the safe use of ionising radiation in medical fields, especially in cancer treatment. Additionally, PIANOFORTE is committed to managing radiological emergencies and developing long-term recovery strategies.

One major aspect of PIANOFORTE is the organisation of open calls at the European level, open to all research teams, not just partners. The first open call, with a budget of EUR 13 million, focused on developing a knowledge base for better understanding disease pathogenesis. Nine projects were selected and commenced in April 2024, with a co-funding rate of 63%. The second call for projects closed on 23 July 2024.

By expanding the pan-European scientific foundation and fostering innovation, PIANOFORTE aims to reinforce the pool of expertise in the radiological protection field. It recognises the importance of integrating AI and Big Data as essential tools for research. Expected benefits include better scientific knowledge, improved implementation of AI and data science, enhanced co-ordination and integration, and greater acceptance of radiological protection strategies among government authorities, implementers, practitioners, civil society and citizens.

Ultimately, PIANOFORTE strives to create a resilient, well-informed society capable of making informed, risk-aware decisions regarding nuclear and technological issues, ensuring the safe and beneficial use of ionising radiation across various sectors.

3.2. Applied research strategy for health risk mitigation in Department of Energy operations

The Office of Domestic and International Health Studies (EHSS-13) is dedicated to conducting research that is directly relevant and responsive to the operational and public health protection needs of the United States Department of Energy (DOE). This includes managing and characterising human health outcomes associated with DOE operations, particularly focusing on hazards like chronic, low-dose ionising radiation.

EHSS-13 has developed an applied research strategy framework aimed at identifying and selecting high-value research areas for the application of resources to specific hazards. This framework emphasises the meaningful characterisation of risks and the development of practical mitigation strategies. The goal of this research strategy is to address critical elements of human health risks associated with hazards across the DOE complex, thereby supporting thriving communities.

The applied research strategy is structured around scientific objectives which outline broad actions needed to support the meaningful characterisation and practical mitigation of identified hazards. Each scientific objective is further defined by key questions that pinpoint critical knowledge gaps essential for effectively meeting these objectives. Each objective also includes an attainable deliverable, resulting from the collected information anticipated to fully or substantially address the scientific objective.

A significant aspect of ensuring the success of this strategy is the incorporation of operational implementation. This involves identifying key collaborative stakeholders and providing education and training resources. The strategy is designed to be adaptable, with the expectation that it will evolve as new information is discovered and synthesised.

EHSS-13's portfolio encompasses both domestic and international health studies. Domestic studies include projects such as the Million Person Study, the Beryllium Associated Worker Registry, the Biological Emergency Response Team, and the US Transuranium and Uranium Registries. International studies feature the Japan Program and the Marshall Islands Program, addressing ionising radiation and biological and chemical threats.

The office aims to transform data into meaningful hazard characterisation and practical mitigation strategies to support thriving communities. Hazards encountered in DOE operations include physical hazards like ionising radiation, acoustic and heat stress/strain, chemical hazards like beryllium, and biological agents. While many hazards are adequately characterised or mitigated, some, such as ionising radiation, require further research. Additionally, new hazards may emerge or evolve, necessitating ongoing assessment.

Overall, EHSS-13's flexible and dynamic research strategy is designed to address the unique health protection needs associated with DOE operations. Its adaptability ensures that the strategy remains effective in protecting human health and supporting thriving communities as new information is discovered and synthesised.

3.3. Fukushima Institute for Research, Education and Innovation in Japan

Thirteen years have passed since the Great East Japan Earthquake and subsequent nuclear disaster at the TEPCO Fukushima Daiichi Nuclear Power Station (FDNPS) in 2011. Nagasaki University has been assisting in reconstruction efforts in the affected areas, though gaps in recovery remain evident in all municipalities surrounding the FDNPS. In 2020, the Great East Japan Earthquake and Nuclear Disaster Memorial Museum was opened in Futaba town to preserve records and transmit lessons learnt from the nuclear

disaster and recovery process for the future. Since its opening, the museum has attracted more than 250 000 visitors and has amassed archives related to other complex disasters, exhibiting them alongside Fukushima-specific materials.

In 2023, the Fukushima Institute for Research, Education and Innovation (F-REI) was established as a world-class centre of excellence for creative restoration. F-REI aims to drive the reconstruction of Fukushima and other parts of the Tohoku region, bolster Japan's scientific and technological capabilities, enhance industrial competitiveness, and contribute to economic growth and improved quality of life. The institute focuses on these key research areas: robotics; agriculture, forestry, and fisheries; energy; radiology and its applications in therapies, pharmaceutical development, and industrialisation; and the collection and dissemination of data and knowledge on nuclear disasters. The museum has pledged to support the fifth research area by utilising its archival materials.

The museum includes an introductory video screening and exhibits on the beginning of the disaster, responses immediately after the nuclear accident, the sentiments of Fukushima citizens, and recovery efforts. It also emphasises radiation risk communication with high school students and the importance of risk reduction. Training courses for Ukrainian students who evacuated to Nagasaki University have been organised, sharing valuable lessons despite the different types of disasters.

Notably, the museum displays items affected by the nuclear disaster, such as untouched blackboards in schools, serving as time capsules of the event. A proposal for future disaster risk reduction is in development, with a mission to collect and disseminate findings about nuclear disasters within the F-REI framework. Lessons from the Fukushima disaster highlight the crucial importance of prompt evacuation and sheltering to prevent fatalities. Accumulating and sharing findings from Fukushima in the field of nuclear disaster medical science is expected to contribute to global disaster risk reduction efforts.

Part 2: Challenges and successes identified by the existing co-ordination networks

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3.4. MELODI

MELODI (Multidisciplinary European Low Dose Initiative) is a European research platform dedicated to addressing the need for expertise in low-dose radiation research. With about 40 institutional members, MELODI aims to strengthen the system of radiological protection by promoting research in relevant areas.

MELODI focuses on several key objectives. One of its primary aims is identifying research priorities in low-dose health risk research. To support this, MELODI has established permanent working groups. One of them maintains and updates the Strategic Research Agenda (SRA) that describes research priorities. Currently, the SRA includes two research topics and two cross-cutting topics (which are relevant for both of the research topics) in low dose or low dose-rate radiation risk research. The topics relate to cancer and non-cancer

diseases. The cross-cutting topics that are relevant to both of these disease categories are individual variation in risk and effects of spatial- and temporal-variation in dose delivery on disease risk. Another working group focuses on education and training and includes mobility grants for early career researchers.

To advance its goals, MELODI organises regular workshops on topics relevant for the field. However, platform members face several challenges, particularly in securing adequate funding. Despite EURATOM-funded projects in radiological protection, there has been a decline in funding in the last years, which poses significant challenges, especially for universities. Consequently, there is a pressing need to convince the European Commission and EURATOM to increase the level of funding for radiological protection research.

By addressing these challenges and continuing its co-ordinated research efforts, MELODI aims to ensure the advancement of knowledge in low-dose radiation effects and the enhancement of radiological protection systems across Europe.

3.5 ALLIANCE

The European radioecology ALLIANCE²⁶ has developed a Strategic Research Agenda (SRA) that outlines a long-term vision for the research needs in radioecology in Europe. This agenda includes maintaining and developing the workforce through education and training and enhancing the associated infrastructure. The strategy takes into account the current state of radioecology research, stakeholder views, identified research needs, and data gaps, proposing a strategic vision for the next 20 years.²⁷ The need to improve mechanistic understanding in radioecological research is driven by three key factors: providing scientific evidence and impact/risk assessments for humans and wildlife, supporting policy evolution and guidance, and addressing shortcomings linked to new technological developments and radioactive releases in the environment, such as SMRs, nuclear decommissioning, nuclear and naturally occurring radioactive material (NORM) waste disposal, legacy sites, and medical uses.

The SRA has evolved since its inception, with the initial agenda written in 2010 and updated in 2013 and 2019. Currently, co-ordinated responses are planned with PIANOFORTE, with further updates expected in the next two years. The agenda emphasises the importance of considering environmental exposure, which is often low-dose and linked to radioecology. It also highlights the need to incorporate stakeholder perspectives on research needs and data gaps.

One of the current challenges is related to low-dose research, focusing on determining ecological effects under realistic exposure conditions. Unlike human radiological protection, there is no unified approach or consensus on the effects of ionising radiation on biota and ecosystems, hindering the development of ecological protection criteria. The strategic vision for the next 20 years aims for radioecology to achieve a thorough mechanistic understanding of radiation effects at different biological organisation levels, including ecosystem integrity. This will involve accurately describing and predicting effects under realistic conditions, with priority research areas encompassing experimental studies (both laboratory and field), statistical data analysis, and mathematical modelling. These studies should link effects from molecular to individual levels, intra-species and

²⁶ For more on the ALLIANCE consult www.er-alliance.eu.

²⁷ Consult the SRA here <https://radioecology-exchange.org/content/strategic-research-agenda>.

inter-species radiosensitivity, interactions with co-stressors, multi-generational responses, and effects at higher biological organisation levels.

The agenda underscores the importance of increasing mobility for students, teachers and funding early career researchers, and developing joint EU MSc programmes. It also stresses the need to identify and create partnerships of excellence for infrastructures and capabilities, maintain a web-based catalogue of infrastructures, and promote the visibility and joint use of existing infrastructures to encourage wider collaboration. Further development of radioecological observatory sites and access to contaminated territories are crucial for studying environmental effects.

A joint roadmap will identify research needs and develop tools to optimise the existing radiological protection system, addressing societal needs and concerns. Priorities in low-dose research include studying radiation-induced effects at multiple levels, investigating intra- and inter-species differences in radiosensitivity, and examining multi-generational responses and long-term biological effects of low radiation doses. Success indicators include evidence of increased integration through SRAs and joint roadmaps, as well as projects and collaborations leading to PhD mobility.

Looking forward, the agenda aims to integrate the ICRP radiological protection system for the next generation, consider new contexts and societal perspectives, incorporate advanced technologies, and update the joint roadmap. Collaboration with experts in related disciplines and the recent creation of a consortium regrouping all European radiation research platforms ([MEENAS](#)) will be instrumental in achieving these goals.

3.6 COHERE

COHERE, the Canadian Organisation on Health Effects from Radiation Exposure, is a partnership between Health Canada and the Canadian Nuclear Safety Commission (CNSC) that was established in 2020 with the development of a Strategic Research Agenda (www.cnsccsn.gc.ca/eng/resources/research/cohere/strategic-research-agenda-cohere/), and followed up with a published vision in 2021 (www.tandfonline.com/doi/full/10.1080/09553002.2021.1941379) (Chauhan et al., 2021). CNSC serves as Canada's nuclear regulator, while Health Canada is responsible for managing risks related to radiation exposure. COHERE's vision focuses on aligning research priorities, enhancing expertise in dosimetry, radiobiology and epidemiology, and disseminating consistent information to Canadians, Indigenous Nations and communities, and stakeholders. The programme is structured around four groups: the Scientific Committee, Program Coordinators, Champions, and the Communication Committee.

COHERE leads various research projects, including those on adverse outcome pathways (AOPs) such as lung cancer (<https://aopwiki.org/aops/272>) (Sherman et al., 2023), vascular remodeling (<https://aopwiki.org/aops/470>) (Kozbenko et al., 2024), learning and memory impairment (<https://aopwiki.org/aops/483>) (Sleiman et al., 2024), cataracts (<https://aopwiki.org/aops/478>) (Carrothers et al., 2024), bone loss (<https://aopwiki.org/aops/482>) (Sandhu et al., 2024), and kidney toxicity (<https://aopwiki.org/aops/437>) (Sadi, 2024), and models radiation interactions with biological systems. Cohort studies involve the national dose registry linkage to cancer, incidence and mortality, subgroups of which include the Canadian fluoroscopy cohort (<https://zablotskaresearchgroup.ucsf.edu/CFCS>), and the Canadian Uranium Workers Study (CANUWS) (www.cnsccsn.gc.ca/eng/resources/research/canadian-uranium-worker-study/). Despite a relatively small network of radiation researchers and funders in Canada, there is a need for national co-ordination to overcome the existing disconnect between research facilities.

National co-ordination would act as a platform to align new activities and ongoing initiatives across Canada, leading to impactful outcomes translatable to policy, improved work efficiencies, enhanced communication to the public, efficient funding use, prevention of project duplication, better international collaboration, and shared resources and facilities. Challenges include time and resource constraints, and the lack of additional resources to support COHERE or the National Coordination Initiative, which hampers member recruitment. However, significant successes have been achieved, including the partnership between CNSC and Health Canada, positive research outcomes, and increased awareness of the government's work on low-dose radiation research.

COHERE's journey over four years has identified many challenges but also highlighted numerous successes, justifying the continued pursuit of larger-scale co-ordination. Investment in initiatives that improve co-ordination of low-dose research supports the mandates of CNSC and Health Canada to protect the health of Canadians and Indigenous Nations and communities.

3.7 PLANET

PLANET, established in Japan in 2017, is a research platform designed to ensure accurate information on the health impacts of low-dose radiation and to facilitate data compilation for public dissemination. Chaired by Dr Kai Michiaki, PLANET serves as a collaborative network of academic and research institutions communicating with regulators and stakeholders.

In 2018, the steering committee created Working Group 1 (WG1) to investigate dose-rate effects through animal experiments. WG1 has conducted integrated analyses of cancer mortality data from B6C3F1 female mice exposed to ¹³⁷Cs rays to estimate the dose-rate effectiveness factor, contributing significant insights into radiation-related carcinogenesis (Doi et al., 2020). WG1 has also conducted reviews of papers on low dose-rate effects research using animal models. These reviews examine animal model research related to cancer development and organise the findings with a focus on how the underlying biological mechanisms of carcinogenesis are involved in the dose-rate effects of radiation carcinogenesis (Suzuki et al., 2023a,b). WG1 recently compared and analysed radiation-related cancer mortality data obtained from Japanese atomic bomb survivors and lifespan studies on mice using a mathematical model of multistage carcinogenesis (Section 3.2; Imaoka et al., 2024).

PLANET has identified four priority categories for Japanese radiation research: understanding low-dose and low-dose-rate radiation risk, individual factors influencing radiosensitivity, biological mechanisms of low-dose and low-dose-rate radiation effects, and integrating epidemiology and biology through mathematical and statistical modelling.

In 2024, PLANET established three new working groups to address various aspects of low-dose radiation research. Working Group 2 (WG2) focuses on dose and dose-rate mapping for radiation risk studies, reviewing existing studies to clarify limitations and perspectives for risk estimation, and defining low-dose and dose-rate ranges. Working Group 3 (WG3) examines species- and organ-specific dose-rate effects, organising data on cell division and death in relation to stem cell turnover, and contributing to the adverse outcome pathway (AOP) project with updated research findings. Working Group 4 (WG4) maps research on radiation-related carcinogenesis, identifying issues that lack research and providing new findings to the AOP project. These new initiatives are summarised in the latest paper (Yamada et al., 2024).

PLANET aims to promote efficient research progress and generate new knowledge on the health effects of low-dose radiation exposure. It seeks to strengthen co-operation among

regulatory organisations, research institutions and stakeholders in Japan, while also developing human resources in radiation risk and protection through joint research and collaboration. The activities of PLANET are expected to improve risk assessment and contribute to the revision of ICRP recommendations.

3.8 Key takeaways and observations

The open discussion brought forward several viewpoints from the participants. Concerns were raised about the feasibility of achieving deliverables through current contributions, questioning funders' priorities and noting that relevance to radiological protection must be demonstrated to secure funding. It was emphasised that funders have limited resources, and research must directly impact their work.

The funding challenges in Europe, despite the support of the European Commission, were highlighted. The necessity of justifying research projects and maintaining flexibility was stressed, especially in light of timely and significant topics like radiological protection during armed conflicts, such as the war in Ukraine.

Risk communication, particularly with members of civil society, was another key focus. The importance of calculating and communicating the meaning of radiation doses in an understandable manner was underscored, emphasising that final decisions should be made by informed members of civil society. A gap in education about low-dose research among students was pointed out, arguing in favour of starting education at earlier stages to ensure that young researchers can make meaningful contributions to the field.

Overall, the discussion highlighted diverse perspectives on funding challenges, the importance of relevance and impact in research, and the critical role of effective risk communication and education in advancing the field of radiological protection.

3.9 Views of research funders and international organisations involved in science-based policies: A roundtable discussion

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This roundtable discussion convened experts to address the current challenges and future directions in radiation sciences. Key themes included the evaluation of extensive data, the professional development of young scientists, the importance of mentorship, and the necessity of international collaboration. The discussion featured contributions from prominent organisations such as the European Commission, the US Environmental Protection Agency, UNSCEAR, the International Commission on Radiological Protection, and the World Health Organization.

Several key themes emerged regarding the current challenges and future directions in the field of radiation sciences, particularly under the auspices of UNSCEAR.

One of the primary challenges identified is the evaluation of the growing volumes of literature and data, which requires significant effort and resources. This was emphasised as a critical area needing attention and strategic response.

The professional development of young radiation scientists was highlighted as a crucial component for the Future Programme of Work for UNSCEAR (2025-2029). Opportunities for collaboration, participation in UNSCEAR sessions, and recognition were noted as essential for fostering this development. Calls were made for in-kind expert contributions to support these efforts.

The importance of mentorship programmes was underscored. An emphasis was placed on the value of involving younger students, including medical undergraduates, to cultivate an appreciation for radiation sciences, even if they do not pursue careers in the field. For current staff, there is a strong encouragement for continuous team education.

The necessity of building up the workforce through training and education was highlighted. This is especially pertinent as some countries consider nuclear energy in their new power policies. Ongoing projects support the mobility and training of students at various academic levels, including for master's and PhD candidates.

The responsibility of ensuring a pipeline of young professionals in the field was addressed. There is a need to fill the skills gap and that is the focus of the ongoing effort of the WHO and the French government to establish the WHO Academy in Lyon to educate the medical community.²⁸ It is important to recognise the benefits, not just the risks, of radiation applications and the need to present workshop outcomes to advance knowledge.

The importance of steering research based on emerging technologies, requirements and activities, especially in areas like radiological protection and low-dose research was also noted. This research requires a long-term perspective and strategic steering to balance outcomes effectively.

The ICRP emphasised the long-term nature of radiation research, citing the slow but steady accumulation of evidence over decades. It is important to maintain a long-term vision for breakthroughs and significant findings.

Discussions also covered strategies for communicating the need for research support to government officials. For example, despite Germany's phase-out of nuclear power, the need for radiological protection remains critical. Engagement with stakeholders, including leveraging research findings from non-NEA countries like China and India, was seen as vital. These countries are encouraged to participate in UNSCEAR's expert groups and national events.

International collaboration was a recurring theme, with an emphasis on protecting members of the public and addressing their concerns to foster better acceptance of radiation technologies. Improving the accessibility and communication of scientific findings to the public and policymakers was seen as essential. Examples such as the webinar series held by the ICRP and International Organization for Medical Physics (IOMP), although technical, were cited as steps in the right direction.²⁹

²⁸ For more on the WHO Academy in Lyon consult www.who.int/about/who-academy.

²⁹ Recording of the webinar can be found here www.youtube.com/watch?v=IAbcnB5Satk.

Overall, the discussion highlighted the need for sustained efforts in mentorship, education, international collaboration and effective communication to ensure the continued advancement in public understanding of radiation sciences.

4. Global perspectives on education and training for radiological protection

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This chapter provides a global perspective on education and training in radiological protection, featuring insights from experts across various institutions. The contributors explore the strategies and initiatives aimed at building competence, ensuring continuity, and fostering innovation in the field. Highlighted topics include the comprehensive approach of SCK CEN in Belgium, the collaborative efforts of HERCA to harmonise radiological protection standards in Europe, the ICRP's Vancouver Call for Action and its mentorship programme, and the Nuclear Energy Agency's initiatives to develop a diverse and inclusive nuclear workforce. These discussions underscore the importance of education, training and international collaboration in advancing radiological protection and addressing the challenges posed by the evolving landscape of nuclear science and technology.

4.1. Competence building in radiological protection to guarantee continuity and innovation

SCK CEN conducts research on all peaceful applications of ionising radiation, addressing societal needs such as climate change, the circular economy and the fight against cancer. Notably, it produces a significant amount of radioisotopes and operates the BR2 reactor, which contributes crucially to cancer treatment improvements. It prioritises the safe operation of nuclear facilities and leverages its extensive 70 years of experience in nuclear research and technology to benefit the healthcare sector.

SCK CEN integrates all its education and training initiatives directly with its research. It aims to develop a sustainable system that builds competences aligned with the needs of the institute and the country. Its strategy focuses on attracting, developing, employing, retaining and maintaining skilled individuals in the right sectors.

The main pillars of its approach include outreach, guiding students and junior researchers, organising academic courses and customised training, providing policy support, and nurturing critical-intellectual capacities for society. Outreach efforts aim to increase general scientific literacy, inform about the applications and risks of radioactivity, and discuss the societal context of radioactivity, including healthcare, electricity production, agricultural benefits, food preservation, and space applications.

SCK CEN collaborates with academic institutions in Belgium to guide students and junior researchers, offering courses such as the BNEN Master-after-Master in nuclear engineering. Its staff also hold part-time positions at universities, further strengthening these academic links. Additionally, it provides policy support in educational and training matters, participating in larger projects to ensure that education and training are well-integrated into broader initiatives.

4.2. Perspectives from the HERCA Working Group on Education and Training

HERCA, the Heads of the European Radiological Protection Competent Authorities, is a voluntary association established in 2007, comprising 56 competent authorities from 32 European countries. Under the chairmanship of Jean-Luc Lachaume from ASN, France, with vice chairs Pilar Lucio Carrasco from CSN, Spain, and Patrick Majerus from MS, Luxembourg, HERCA aims to ensure a high level of radiological protection across Europe. The organisation operates within the framework of the EURATOM Treaty and focuses on significant regulatory issues of common interest.

To achieve its goals, HERCA maintains a European network of chief radiological protection regulatory authorities, promotes the exchange of ideas and experiences, and develops a unified approach to radiological protection and its regulatory transposition. The organisation is structured into various working groups, including those dedicated to education and training, emergencies, medical applications, natural radiation sources, research and industrial sources and practices, and veterinary applications. Additionally, the HERCA Board has established task forces and networks such as the Occupational Dose Collection and Registration and Reporting to address issues of common interest. Stakeholders like the EC, IAEA, NEA and UNSCEAR actively participate in HERCA meetings.

From its inception, HERCA has prioritised education and training in radiological protection. The Working Group on Education and Training (E&T) focuses on the implementation of the Radiation Protection Expert (RPE) and Radiation Protection Officer (RPO) concepts. The group includes participants from 18 HERCA member states and is mandated to investigate the application of a graded approach for RPE and RPO assignments, identify common criteria for evaluating their competences, and define concepts of on-the-job training and work experience related to their recognition.

Moreover, the Working Group on E&T aims to determine how a graded approach can be applied to training and retraining activities for RPEs and RPOs. The related analysis indicates that most member states have implemented the RPE and RPO concepts as defined in the EU BSS. Currently, the group is drafting a document on best practices for using a graded approach in the implementation of these concepts across HERCA members.

4.3. The ICRP Vancouver Call for Action and Mentorship Programme

The International Commission on Radiological Protection (ICRP) has expressed significant concern over the potential consequences of inadequate investment in training, education, research and infrastructure related to radiation sciences and radiological protection. This shortfall could severely compromise society's ability to manage radiation risks effectively. In response, the ICRP issued the "Vancouver Call for Action" at the 6th International Symposium on the System of Radiological Protection in Vancouver, Canada. This initiative urges national governments, funding agencies, national research laboratories, scientific institutions and universities to bolster their efforts in this domain. The call highlights the necessity of strengthening resources for radiological protection research allocated by governments and international organisations, developing comprehensive undergraduate and graduate programmes at universities, and using plain language when engaging with the public and decision makers. Additionally, it emphasises the importance of fostering general awareness of the proper uses of radiation and radiological protection through education and training.

As a contribution to the Vancouver Call for Action, the ICRP has established the ICRP Mentorship Programme, which has been operational since 2019. This programme aims to provide professional development opportunities and insights into the work of the ICRP

through active participation in Task Groups. Since its inception, 72 mentees have participated in the programme, with 61 currently involved. Mentees, who may be university students or early career professionals from various sectors, are assigned specific tasks such as literature reviews, developing data spreadsheets, performing calculations and simulations, conducting measurements, supporting internal surveys, and participating in paper writing. The mentorship programme, which currently operates within 15 of the 30 active Task Groups, ensures the engagement of young people, bringing new ideas to the field of radiological protection. The ICRP encourages other radiological protection organisations to adopt similar initiatives to strengthen expertise in the radiological protection workforce worldwide.

4.4. Nuclear Energy Agency education initiatives




The Nuclear Education, Skills and Technology (NEST) 2035 Project aims to build a diverse, inclusive, and gender-balanced nuclear workforce by enhancing and accelerating existing NEA initiatives. The project provides added value and benefits to participants, including a fast track to leadership roles. This initiative supports the 2023 OECD Council Recommendation on Improving Gender Balance in the Nuclear Sector.

Ongoing NEST projects include hydrogen containment experiments for reactor safety, small modular reactors, and advanced remote technology and robotics for decommissioning. NEST fellows plan to join the Summer School on AI for Nuclear, to be held in Halden, Norway, in September 2024.

The NEA launched the Global Forum on Nuclear Education, Science, Technology and Policy in January 2021. The forum engages with academic institutions worldwide to develop the next generation of nuclear science experts and provides a framework for co-operation, addressing international policy challenges and highlighting emerging issues through symposia.

The global forum has seven different working groups as seen in Table 4.1:

Table 4.1 Nuclear Energy Agency Global Forum areas of work

<div>  Nuclear Energy Agency  </div>						
<div>  Global Forum areas of work </div>						
<div> Council of Advisors (35 members from 20 academic institutions in 13 countries) </div>						
Governs the Global Forum and defines its programme of work						
Working Group 1 Gender Balance in Nuclear Technology & Academic Workforces	Working Group 2 Future of Nuclear Engineering Education	Working Group 3 Relationship Between Nuclear Energy & Society	Working Group 4 Innovations in the Nuclear Sector	Working Group 5 Re-Establishing Nuclear Law Education Programmes	Working Group 6 Building a pipeline of STEM professionals <i>(NEW)</i>	Working Group 7 Developing an International Curriculum for the Back End of the Nuclear Fuel Cycle <i>(NEW)</i>
<ul style="list-style-type: none"> Promotion of nuclear engineering and technology programmes to women Inclusion and leadership of women in these fields Encouraging men as vocal allies 	<ul style="list-style-type: none"> Tools and digital technologies for nuclear education Multidisciplinary approaches in nuclear education Open Science: Educational benchmark activities 	<ul style="list-style-type: none"> Research benefits of nuclear; establishing affective associations Research values of nuclear community Research future nuclear scenarios and share with sectors of society and policy 	<ul style="list-style-type: none"> Large reactors; modular, small and micro reactors; Production of alternative energy vectors Integration of nuclear with renewables, storage and flexible grid systems 	<ul style="list-style-type: none"> Assist in the development of graduate-level nuclear law programmes and expand the number of qualified educators to recruit a new generation of nuclear law professionals. 	<ul style="list-style-type: none"> Engaging with secondary school students and their teachers Building awareness of STEM career options Provide education about nuclear science and technology 	<ul style="list-style-type: none"> Analyse global programs for theoretical and practical DGR integration. Document methods for project-based and lab-based courses.

Governing the global forum and its programme of work is a council of advisors consisting of 35 members from 20 academic institutions in 13 countries.

The NEA, in collaboration with the OECD Development Centre, is working on the "Our Common Journey" project to create a policy dialogue platform for knowledge sharing and capacity building in nuclear deployment, promoting safety, security and gender balance. This initiative supports Africa's sustainable economic development. NEA Director-General William D. Magwood, IV highlighted this effort at an event during the African Union Summit in Ethiopia in February 2024.

The discussion emphasised the need for co-ordinated actions among young professionals, facilitated by NEA schools like the IRPS summer course in Stockholm. Despite the lack of financial support for the ICRP mentee programme, it continues to operate, highlighting the commitment to nurturing the next generation of professionals. The inclusion of PhD students in research projects and collaboration with Belgian universities was encouraged to ensure a comprehensive approach to education and training in the field.

4.5. Key takeaways and observations

The primary objective of the HLG-LDR is to enhance the effectiveness and efficiency of research in radiological protection policy, regulation and implementation by fostering global networking for co-ordinating ongoing and future low-dose research projects. The group is committed to effective information exchange techniques and is particularly focused on promoting the AOP and the low-dose register within the RP community to ensure their active contribution. During the interactive part of the session, participants discussed various efforts by the HLG-LDR topical group on communication

The review of activities highlighted efforts in Canada and the United States. In the United States, there have been presentations before governmental agencies and professional organisations, while Canada has initiated monthly webinars on the biological and health effects of low-dose radiation for over a year. These webinars aim to bring together the research and radiological protection communities to discuss relevant topics. In other regions, the growing importance of capacity building and skills development in nuclear newcomer states in Africa was also highlighted by the NEA.

Workshop participants addressed various stages of the recruitment and training pipeline, emphasising the importance of broad co-ordination to connect leaders with outreach, education and training programmes. The need for meaningful work to retain and motivate students was highlighted, with an emphasis on the role of training in setting standards for radiation professionals. The discussions also noted that while training can establish standards, these should ultimately be linked to competencies rather than the training itself.

Mentorship programmes, particularly within the ICRP, were discussed, with a focus on tasks related to medical applications under committee 3.

The group is also exploring ways to incentivise the use of the low-dose register and developing resources for outreach and education through social media. Educational programmes are being targeted at the next generation of risk assessors, focusing on the AOP process and creating mentorship opportunities for young scientists.

5. Structuring an open dialogue on low-dose research within the radiological protection community and beyond

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This chapter discusses the importance of structuring an open dialogue on low-dose research within the radiological protection community and beyond. Contributors from national institutions and international organisations, including Johns Hopkins University, the Nuclear Energy Agency, the Canadian Nuclear Safety Commission, and the US Environmental Protection Agency, shared their insights on communication strategies, mentorship programmes, and educational initiatives. The focus was on fostering collaboration, enhancing understanding and improving the effectiveness of research and communication in the field of low-dose radiation.

5.1. Efforts of the HLG-LDR topical group on communication

The NEA High-Level Group on Low-Dose Research aims to support radiological protection policy, regulation and implementation by enhancing the effectiveness and efficiency of research through global networking. This involves co-ordinating ongoing and future low-dose research projects. Specifically, the HLG-LDR seeks to establish a global network to facilitate collaboration among low-dose/low-dose rate ionising radiation research programmes, promoting the collective sharing of information and resources. The communications topical group within HLG-LDR plays a crucial role in this effort by facilitating the exchange of research objectives and results with stakeholders, encouraging collaboration, and engaging in outreach and education activities related to the Global Register and the application of adverse outcome pathways in low-dose radiation decision making.

The mandate of the HLG-LDR includes developing approaches and tools to share information on ongoing and planned research worldwide and to better structure the existing knowledge on radiation-induced effects on humans and non-human species. These tools are used to identify research gaps in the field of low-dose/low-dose rate effects and develop mechanisms for prioritisation and co-ordination worldwide. Additionally, the group aims to share experiences in research planning, implementation and result reporting with decision makers and other relevant stakeholders.

The communications topical group within HLG-LDR plays a crucial role in this effort by facilitating the exchange of research objectives and results with stakeholders, encouraging collaboration, and engaging in outreach and education activities related to the Global Register of Low-Dose Research Projects and the application of adverse outcome pathways in low-dose radiation decision making.

Looking ahead, the HLG-LDR plans to incentivise contributions to, and utilisation of, the Global Register of Low-Dose Research Projects. It aims to develop resources for outreach

and education through social media, create educational programmes for the next generation of risk assessors focusing on the AOP process, and establish a mentorship programme for young scientists. Other initiatives include organising additional workshops and webinars to bring together researchers and regulators, continuing collaboration with other international groups such as UNSCEAR, ICRP, EPRI, NCI and Research Platforms, and co-ordinating existing animal biobanks potentially through a community of practice. The group also intends to prepare at least one white paper outlining communication strategies and, if possible, communication goals.

5.2. The role of NEA schools in enhancing understanding of low-dose radiation issues

The NEA International Radiological Protection School (IRPS) and the Nuclear Risk Communication Training Course (RCTC) are educational initiatives aimed at building capacity and enhancing knowledge in the field of nuclear and radiological protection. Established in 2018 through a collaboration between the NEA, the Swedish Radiation Safety Authority (SSM), and Stockholm University, the IRPS aims to provide early to mid-career professionals with an in-depth understanding of the radiological protection system, its application in various sectors, and its evolving nature based on lessons learnt. The school has introduced an online platform to support learning and preserve knowledge, implemented hybrid arrangements to increase participation from less developed countries, and shifted follow-up surveys to Survey Monkey to facilitate feedback analysis. Practical aspects have been reinforced with more case studies and a mini-workshop. Key topics covered include the foundation of the international RP framework, the state of the art in RP sciences, a holistic approach to justification and optimisation of protection involving ethics and stakeholder involvement, and current challenges such as armed conflict and new technologies. The sustainability of the initiative was strengthened by a multi-year agreement to host this school annually until 2028.

The RCTC, developed under the NEA Committee on Nuclear Regulatory Activities (CNRA) Expert Group on Public Communication of Nuclear Regulatory Organisations (EGPC), was initiated as an outcome of the NEA's 2nd Stakeholder Involvement Workshop on Risk Communication in 2019. Its primary aim is to improve the effectiveness of risk communication to enhance public understanding and build trust. The target audience includes professionals working in nuclear regulatory organisations, technical scientific support organisations, and licensees responsible for communicating or engaging with the public and decision makers about nuclear and radiological risks. The course is intended to evolve and be offered on an ongoing basis. Previous sessions were held in Bratislava, Slovak Republic in 2022, in Abu Dhabi, United Arab Emirates in 2023 and in Ottawa, Canada on 28-31 October 2024. Future host countries are being sought.

5.3. The art of communicating low-dose risk in a regulatory setting

An important pillar of the Canadian Nuclear Safety Commission mandate is to disseminate objective scientific, technical and regulatory information to the public and Indigenous Peoples (Nuclear Safety and Control Act). Over the years, strategies for communicating radiological risk have evolved dramatically, moving towards social media as an important tool. Best practices for effective risk communication include involving the public early as a partner, listening to the public's specific concerns, being open and honest, collaborating with credible partners, addressing the needs of the media, speaking clearly and with compassion, and evaluating past efforts (NEA, 2016; Hyer and Covello, 2017).

Science communication is a distinct discipline where messages are crafted for specific audiences. Similarly to the general scientific method, science communication begins with data collection and can involve qualitative and quantitative analysis. Within science communication, a challenge specific to radiation risk communication is that experts define risk as a product of probability and consequence (Goodfellow et al., 2011), while members of the public consider additional factors, such as catastrophic potential, familiarity, understanding, uncertainties, controllability, voluntariness of exposure, effects on children and future generations, identifiable victims, dread, trust in institutions, media attention, accident history, equity, benefits, reversibility and origin (Covello and Sandman, 2001).

Lessons learnt from past nuclear and radiological accidents have demonstrated that radiation risk communication is more effective during non-emergency situations, highlighting the importance of establishing trusting relationships in advance (NEA, 2021b; Perko, 2016). Despite widely understood best practices, effective risk communication remains challenging. These challenges arise from the difference between how experts define risk and how individuals perceive it. To improve radiological risk communication, interdisciplinary research combining scientific evidence from radiation research with social science and humanities research on perceived risk is planned. This research is anticipated to significantly impact the international radiological protection community by generating new knowledge on radiation risk perception, potentially leading to updated guidance that better reflects the importance of risk perception in communication and stakeholder engagement.

Improving expert understanding of public perceptions, enhancing communication and engagement practices, and providing data to aid in modelling response effectiveness are key goals. By enhancing dialogue and communication, it is possible to decrease fear associated with radiation, build trusting relationships, and improve engagement processes. The planned research will include an Indigenous methodology (e.g. storytelling, sharing circle) (Drawson et al, 2017) which offers valuable and unique ways of exploring science that are different from western methods.

In conclusion, honest transparency is crucial in building trust, and collaboration, guided by the seven cardinal rules of risk communication, is highly effective. Additionally, incorporating large images in presentations can be more engaging, as extensive bullet points may detract from the audience's attention to the speaker. Through these efforts, authorities can provide more meaningful, tailored information to specific audiences, empowering individuals to make informed radiation-related decisions.

5.4. EPA's perspective on radiation risk for Superfund sites

The US EPA issued guidance entitled "Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination" (OSWER No. 9200.4-18, 22 August 1997). This guidance clarifies the establishment of protective cleanup levels for radioactive contamination at CERCLA sites, reiterating that cleanups of radionuclides are governed by the risk range for all carcinogens established in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) when Applicable or Relevant and Appropriate Requirements (ARARs) are not available or sufficiently protective. Cleanups should generally achieve a risk level within the 10⁻⁴ to 10⁻⁶ carcinogenic risk range based on the reasonable maximum exposure for an individual, including exposures from all potential pathways and media (soil, groundwater, surface water, sediment, air, structures, etc.). The guidance also lists radiation standards likely to be used as ARARs for establishing cleanup levels or conducting remedial actions.

Jon Richards, in his discussion on the US EPA's perspective on radiation risk for Superfund sites, highlighted how the EPA addresses site cleanup under several laws and programmes, with many sites originating from historical releases or commercial facilities. Given that only 66 out of 1 304 total Superfund sites are radioactively contaminated, the original focus of the Superfund remedial programme has been on chemicals. However, radiation is effectively integrated within the Superfund Remedial Program's framework.

CERCLA cleanup levels are often determined by ARARs. For non-carcinogens, cleanup levels should not result in adverse effects to human health, accounting for higher radiation from global and natural backgrounds. Common radiation ARARs include NRC Low-Level Waste standards and the effective dose equivalent of 0.15 mSv/yr as outlined in 1997 guidance. The EPA sets the standard for safe drinking water based on IRPC recommendation 2 from 1957.

Jon Richards also referenced the 2014 risk assessment for Maxey Flats, which updated the exposure duration from 30 to 26 years based on the latest census data and provided an overview of current EPA guidance for radiation risk assessment. The process of converting radiation dose is crucial for determining the amount of radionuclide externally exposed, ingested or inhaled. Superfund radiation guidance is supported by tools such as the Rad PRG Calculator and the EPA's Blue Book risk models, which project radiogenic cancer risks for the US population. Despite progress, the harmonisation of these standards and guidelines remains an ongoing effort.

5.5. Enhancing understanding and communication in low-dose radiation research: A roundtable discussion

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This roundtable discussion delved into multiple facets of radiological protection, stakeholder concerns, and effective communication strategies.

One speaker noted that findings are currently well-aligned with regulatory needs and emphasised the importance of national-level participation in radiological protection initiatives. Another participant highlighted that stakeholder concerns about radiation are influenced by more than just the perceived size of the risk, suggesting the need to better understand what policymakers and the radiological protection community consider valuable.

The challenge of educating scientists on how to communicate effectively was brought up, emphasising the need for a two-way dialogue. The importance of being transparent with the public about the limitations of what can be done and what is known was emphasised. The consensus-based nature of some organisations was mentioned as a potential challenge in achieving effective communication.

Long-term cleanups were discussed, with a call for greater inclusion of experts in meetings to avoid working in silos. The importance of peer reviews was stressed, and practical steps for engaging with the community were shared, including the creation of educational

materials like fact-sheets designed for an 8th-grade reading level. Special considerations were mentioned for working with different cultures, including developing customised fact-sheets for specific tribes.

Reflecting on past communication strategies post-Chernobyl, it was acknowledged that previous attitudes often underestimated the public's intelligence, leading to poor communication practices. The value of being present on the ground and listening to local colleagues to understand community needs was emphasised.

There was a critique of the assumption that the public only requires brief safety assurances. The need for detailed regulatory oversight reports and the inclusion of public feedback in these reports was highlighted. It was noted that comprehensive reports are crucial for experts who rely on this information to stay informed, and the availability of detailed data sets was finally achieved after years of advocacy.

On low-dose research, it was recognised that without biomarkers, epidemiological studies alone cannot provide all the answers. The role of radiobiology in addressing these gaps was emphasised. The discussion underscored the vast amount of data on lower doses, which can lead to different conclusions based on the endpoints studied. Participants agreed that while new knowledge would continue to emerge, the current evidence supports the notion that lower doses correspond to lower risks. There was also a call for more research into the variability of risks, particularly how they influence different populations and the best methods for communicating these risks.

The roundtable highlighted the need for better risk communication, tailored educational materials, and more inclusive and detailed regulatory reporting. The importance of continued research into low-dose radiation effects and the variability of risk perceptions was also emphasised.

During the interactive discussion with the audience, one participant emphasised the unique challenges posed by low doses resulting from nuclear detonations, noting that survivors would experience health effects of radiation exposures distinct from those caused by the detonation itself. The participant highlighted the common misconception that low-dose exposure is solely linked to cancer, pointing out the need for greater awareness of other potential health effects. Insights were sought on effective approaches to increase awareness of this unique situation.

Another participant noted the ongoing efforts to define and address the meaning of low-dose exposure, underscoring the importance of stakeholder involvement in risk communication. Feedback was emphasised regarding the expectations from low-dose research and the key messages that should be communicated. Reference was made to the results of recent epidemiological studies, with a focus on identifying the main highlights that researchers should include in the communication strategy outlined in a forthcoming white paper.

6. Workshop key takeaways

During the concluding session, several key topics and notes were highlighted. Firstly, the necessity for funding was emphasised, particularly for research, mobility and training events. Communication activities targeting the young public were also noted as a means to attract new talent and provide positive publicity. The challenges of explaining and communicating low-dose radiation to the public were discussed, with an emphasis on the complexity of conveying risk and the importance of presenting it as a grey area rather than a definitive truth. The evolving nature of research was acknowledged, noting that each answer often brings new questions.

The progress made since the 1960s in understanding cancer risks associated with radiation was highlighted, and the importance of synthesising workshop results to demonstrate their viability was underscored. Integrating these results remains challenging, but examples of successful integration were noted. Quantifying the magnitude of risk, rather than presenting a binary risk/no-risk message, was deemed crucial. The evolution of work programmes, such as those by UNSCEAR, was seen as a positive development. The potential for a website to consolidate training initiatives and a focus on training programmes related to cancer mechanisms and communication was suggested.

Actionable items highlighted during the workshop include the below:

- White paper: Develop a white paper summarising the workshop discussions and outlining communication strategies and goals. Clearly define the narrative, whether emphasising low or high risks. The language of the paper should be clear in its definition of opportunities and challenges.
- Educational website: Create a website with educational activities.
- Communication strategies: Reiterate known and well-understood information about low doses in reports while acknowledging the gaps in knowledge.
- Funding: Secure funding for research, mobility and training events.
- Youth engagement: Develop communication activities targeting the young public to attract new talent and provide publicity.
- Training initiatives: Consolidate training initiatives and focus on programmes related to cancer mechanisms and communication.

The workshop underscored the importance of continuous research, effective communication, and collaborative efforts in advancing the understanding and management of low-dose radiation risks. By addressing the identified action items, the radiological protection community can enhance its capacity to communicate risks, engage stakeholders, and support the next generation of researchers and professionals in the field.

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Annex A: Workshop agenda

Day 1

Setting the Scene on the Issue of Low-Dose Research

Welcome addresses

William D. Magwood, IV, Director-General, Nuclear Energy Agency (NEA)

Darcy Campbell, Principal Team Lead, Radiation Safety, Electric Power Research Institute (EPRI)

The co-ordination strategy and related activities of the NEA CRPPH High-Level Group on Low-Dose Research

Dominique Laurier, Chair of the HLG-LDR, Institute of Radioprotection and Nuclear Safety, France

The EPRI view and actions in global co-ordination of low-dose research: The International Dose Effects Alliance

Borja Bravo, Principal Technical Leader, Radiation Safety, Electric Power Research Institute (EPRI)

Session 1: Synthesis of Recent Research Findings and Their Potential Impact on Radiological Protection and Public Health

Unravelling biological mechanisms and cancer outcomes from low-dose and low-dose rate radiation exposure

Simon Bouffler, Deputy Director for Radiation Protection Sciences, UK Health Security Agency, United Kingdom

Radiation Effects on the Eye: Evidence and Significance

Nobuyuki Hamda, Senior Research Scientist, Central Research Institute of Electric Power Industry (CRIEPI), Japan

Neurocognitive Consequences of Low-Dose Exposure

Katalin Lumniczky, Head, Unit of Radiation Medicine, National Public Health Centre, Hungary

Low-Dose Exposure and Diseases of the Circulatory System Effects

Simone Mörtl, Head of Radiation Biology, Federal Office for Radiation Protection (BfS), Germany

Overview of Research Progress in Understanding Transgenerational Effects of Low-Dose (rate) Exposure on Living Organisms

[Olivier Armant](#), Group Leader, Laboratory of Ecology and Ecotoxicology of Radionuclides, Institute for Radioprotection and Nuclear Safety (IRSN), France

[Overview of Results from Epidemiological Childhood CT-Scan Studies](#)

[Marie-Odile Bernier](#), Epidemiologist, Institute for Radioprotection and Nuclear Safety (IRSN), France

[Open Discussion with Participants](#)

[Moderated by Jacqueline Garnier-Laplace](#), European Radiation Protection Strategy Co-ordinator, Institute for Radioprotection and Nuclear Safety (IRSN), France

[Synthesis of Recent Epidemiological Studies on Workers About Relationships Between Exposure and Health Effects \(cancer and non-cancer\)](#)

[David Richardson](#), Professor of Environmental and Occupational Health, University of California, Irvine, United States

[Overview of the Fukushima Health Management Survey](#)

[Seiji Yasumura](#), Director, Radiation Medical Science Center, Fukushima Medical University (FMU), Japan

[Update on US DOE Radiation Health Studies Program](#)

[Joey Zhou](#), Senior Epidemiologist, US Department of Energy, United States

[Biological Effects of Tritium Exposure, Including Life Span Study in Mice](#)

[Marcelo Vazquez](#), Section Head Radiobiology, Canadian Nuclear Laboratories (CNL), Canada

[Open discussion with participants](#)

[Moderated by Rodolphe Gilbin](#), Lead, Radiation Protection of Populations and the Environment Service, Institute for Radioprotection and Nuclear Safety (IRSN), France

Session 2: Approaches/tools to improve research strategy

Part 1: Adverse outcome pathways (AOPs) and modelling approaches

[AOPs in Radiological Protection with an update of activities of the HLG-LDR Rad/Chem AOP Joint Topical Group](#)

[Vinita Chauhan](#), Chair, Rad/Chem AOP joint group, Health Canada, Canada

[AOPs in ecotoxicology and path forward](#)

[Knut Erik Tollefsen](#), Co-Chair, Rad/Chem AOP joint group, Norwegian University of Life Sciences (NMBU), Norway

[AOP-helpFinder: A tool for Exploration of the Literature to Support Adverse Outcome Pathways Development](#)

[Thomas Jaylet](#), PhD student, Université Paris Cité, France

Human-Mouse Comparison of the Multistage Nature of Radiation Carcinogenesis in a Mathematical Model

Tatsuhiko Imaoka, Group Leader, Department of Radiation Effects Research, National Institute for Quantum and Radiological Sciences (QST), Japan

Part 2: Epidemiological Approaches

High-Throughput Genome Science: Towards the Strategic Goals of the Radiation Effects Research Foundation

Dr Preetha Rajamaran, Vice Chair, Board of Directors, Radiation Effects Research Foundation (RERF)

Molecular Epidemiology Provides New Insights Into Cancer Risk After Low-Dose Radiation Exposure: Thyroid Cancer After the Chernobyl Nuclear Power Plant Accident

Lindsay Morton, Director, Radiation Epidemiology Branch, National Institute of Health/National Cancer Institute, United States

Part 3: Existing databases, tissue archives, infrastructures

The NEA Global Register of Low-Dose Research Projects: Its Place Among Other Radiobiology Databases and Archives

Dmitry Klovov, Chair, Global Register topical group, IRSN, France

Outcomes of the PIANOFORTE Infrastructure Workshop

Liz Ainsbury, co-lead, PIANOFORTE Working Party, UKHSA, United Kingdom

Open Discussion with Participants

Moderated by: [Corinne Mandin](#), Lead, Radiation Epidemiology Group IRSN, France and [Nobuyuki Hamada](#), Senior Research Scientist, Central Research Institute of Electric Power Industry (CRIEPI), Japan

Closure of day 1

Borja Bravo and [Dominique Laurier](#), workshop chairs

End of day 1

Workshop Reception

Day 2

Opening of day 2

Borja Bravo and Dominique Laurier, workshop chairs

Session 3: Addressing weaknesses in low-dose research co-ordination and governance

Experiences from co-ordinated project managers

PIANOFORTE – The European Partnership

Jean-Christophe Gariel, Deputy Director General, IRSN, France

A Long-Term Research Strategy for the Department of Energy's Office of Domestic and International Health Studies

S. Robin Elgart, Director, Office of Domestic and International Health Studies, US Department of Energy, United States

The Recently Established Fukushima Institute for Research, Education and Innovation (F-REI) in Japan: Focus on the F-REI's Fifth Research Area "Accumulation and Dissemination of Data and Knowledge on Nuclear Disaster"

Noboru Takamura, Professor, Department of Global Health, Medicine and Welfare, Atomic Bomb Disease Institute, University of Nagasaki, Japan

Challenges and Successes Identified by the Existing Co-Ordination Networks

MELODI

Andrzej Wojcik, Head, Centre for Radiation Protection Research, Stockholm University, Sweden

ALLIANCE

Rodolphe Gilbin, Lead, Radiation Protection of Populations and the Environment Service, IRSN, France

COHERE

Julie Leblanc, Radiation and Health Sciences Officer, Canadian Nuclear Safety Commission (CNSC), Canada

PLANET

Yutaka Yamada, Researcher, Department of Radiation Effects Research, National Institute for Quantum and Radiological Sciences (QST) Japan

Open discussion with participants

Moderated by: Marie-Claude Gregoire, Head of Directorate, Isotopes, Radiobiology and Environment, Canadian Nuclear Laboratories, Canada

Roundtable on the Views of Research Funders and International Organisations Involved in Science-Based Policies

Moderated by:

Marie-Claude Gregoire, Head of Directorate, Isotopes, Radiobiology and Environment, Canadian Nuclear Laboratories, Canada

Panellists:

Angelgiorgio Iorizzo, Research Programme Officer – Policy Officer, DG Research and Innovation, European Commission

David Borrego, Physical Scientist, Center for Science and Technology, US Environmental Protection Agency, United States

Borislava Batandjieva-Metcalf, Secretary, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

Werner Rühm, Chair, International Commission on Radiological Protection (ICRP)

Ferid Shannoun, Scientist, Radiation and Health Unit, World Health Organization (WHO)

Session 4: Global Perspectives on Education and Training for Radiological Protection

Competence Building in Radiological Protection to Guarantee Continuity and Innovation

Michèle Coeck, Director, Academy for Nuclear Science and Technology, SCK CEN, Belgium

Perspectives from the HERCA Education and Training Working Group

Sotiris Economides, Special Scientific Personnel, Regional Training Centre in Europe, Greek Atomic Energy Commission, Greece

The ICRP Vancouver Call for Action and Mentorship Programme

Werner Rühm, Chair, International Commission on Radiological Protection (ICRP)

NEA Initiatives: The Nuclear Education, Skills and Technology (NEST) Framework, the NEA Global Forum on Nuclear Education, Science, Technology and Policy

Elisa De Sisti, Junior Analyst, Nuclear Education, Training, Outreach and Knowledge Management, Nuclear Energy Agency

Open discussion with participants

Moderated by Julie Leblanc, Radiation and Health Sciences Officer, Canadian Nuclear Safety Commission (CNSC), Canada

Session 5: Structuring an Open Dialogue on Low-Dose Research Within the Radiological Protection Community and Beyond

Efforts of the HLG-LDR Topical Group on Communication

Paul Locke, Chair, Topical group on Communication Strategy, Johns Hopkins University, United States

IRPS and Risk Communication Course: How the NEA schools Contribute to a Better Understanding of Low-Dose Issues

Lucas Martiri, Radiological Protection Specialist and **Minori Kato**, Senior Specialist, Nuclear Energy Agency

The Art of Communicating Low-Dose Risk in a Regulatory Setting

Julie Burt, Radiation Biologist, Canadian Nuclear Safety Commission, Canada

EPA's Perspective on Radiation Risk for Superfund Sites

Jon Richards, Radiation Expert and Project Manager, Superfund and Emergency Management Division, US Environmental Protection Agency (EPA), United States

Roundtable discussion

Moderated by:

Paul Locke, Chair, Topical group on communication strategy, Johns Hopkins University, United States

Panellists:

Werner Rühm, Chair, International Commission on Radiological Protection (ICRP)

Kathryn Higley, President, National Council on Radiation Protection and Measurements (NCRP), United States

Deborah Oughton, Professor, Centre for Environmental Radioactivity, Norwegian University of Life Sciences (NMBU), Norway

Maria Antonia López, President of Spanish Society for Radiological Protection, Spain

Stuart Walker, Regulator, EPA Superfund Office, US Environmental Protection Agency, United States

Pippa Feinstein, Coordinator, Nuclear Transparency Project, Canada

Open Discussion with Participants

Moderated by: **Paul Locke**, Chair, Topical group on communication strategy, Johns Hopkins University, United States

Closing Remarks and Conclusion

Borja Bravo and **Dominique Laurier**, workshop chairs

Tamara Yankovich, Deputy Head of Human Aspects of Nuclear Safety, Nuclear Energy Agency

End of Workshop
