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MEMORANDUM

ICRP workshop on the review and revision of the system of radiological protection: a focus on research priorities—feedback from the international community

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Abstract

In September 2022, the International Commission on Radiological Protection (ICRP) organised a workshop in Estoril, Portugal, on the 'Review and Revision of the System of Radiological Protection: A Focus on Research Priorities'. The workshop, which was a side event of the European Radiation Protection Week, offered an opportunity to comment on a recent paper published by ICRP on areas of research to support the System of Radiological Protection. Altogether, about 150 individuals participated in the workshop. After the workshop, 16 of the 30 organisations in formal relations with ICRP provided written feedback. All participants and organisations followed ICRP's view that further research in various areas will offer additional support in improving the System in the short, medium, and long term. In general, it was emphasised that any research should be outcome-focused in that it should improve protection of people or the environment. Many research topics mentioned by the participants were in line with those already identified by ICRP in the paper noted above. In addition, further ideas were expressed such as, for example, that lessons learned during the COVID-19 pandemic with regards to the non-radiological social, economic and environment impacts, should be analysed for their usefulness to enhance radiological protection, and that current protection strategies and application of current radiological protection principles may need to be adapted to military scenarios like those observed recently during the military conflict in the Ukraine or the detonation of a nuclear weapon. On a broader perspective, it was discussed how radiation research and radiological protection can contribute towards the Sustainable Development Goals announced by the United Nations in 2015. This paper summarises the views expressed during the workshop and the major take home messages identified by ICRP.

1. Introduction

Current international regulations on radiological protection are based on recommendations developed by the International Commission on Radiological Protection (ICRP). Since 1928, ICRP has issued more than 150 publications in which these recommendations are described. While many of those publications deal with specific aspects relevant for radiological protection, some of the recommendations are more general in nature and describe the fundamental concepts on which the System of Radiological Protection (the 'System') of ICRP is based. Those general recommendations include the 1928, 1931, 1934, 1937, 1950, and 1954 and 1956 Recommendations, and ICRP *Publication 1* (ICRP 1959), *6* (ICRP 1964), *9* (ICRP 1966), *26* (ICRP 1977), *60* (ICRP 1991), and *103* (ICRP 2007). An update of these general recommendations is now required because, for example, the scientific evidence of radiation-related health effects on which the System is based, as well as social values and the risk perception of the society, progress with time.

For this reason, ICRP has recently embarked on the process to review the most recent general recommendations ICRP *Publication 103* (ICRP 2007) aiming to develop them further and make them fit for the future. Clearly, this process will be of relevance for the radiological protection community all over the world, and it will require a huge effort as it includes all aspects of radiological protection. ICRP therefore encouraged the international community to join this effort and, together with ICRP, develop a modern framework for radiological protection to be used for several decades to come.

For this endeavour, it is instrumental that ICRP maintains relations with other international organisations with an interest in radiological protection. Organisations currently in formal relations with ICRP are: Conference of Radiation Control Program Directors, European ALARA Network (EAN), European Alliance for Medical Radiation Protection Research (EURAMED), European Association of Nuclear Medicine (EANM), European Commission (EC), European Federation of Organisations for Medical Physics (EFOMP), European Nuclear Installations Safety Standards Initiative (ENISS), European Platform on Preparedness for Nuclear and Radiological Emergency Response and Recovery (NERIS), European Radiation Dosimetry Group (EURADOS), European Radioecology Alliance (ALLIANCE), European Society of Radiology (ESR), European Training and Education in Radiation Protection Foundation (EUTERP), Heads of the European Radiological Protection Competent Authorities, Ibero American Forum of Radiological and Nuclear Regulatory Organisations (FORO), International Commission on Non-Ionizing Radiation Protection (ICNIRP), International Electrotechnical Commission (IEC) Electrical Equipment in Medical Practice (IEC/TC62), IEC Nuclear Instrumentation (IEC/TC45), International Nuclear Workers' Unions' International Network, Information System on Occupational Exposure, International Atomic Energy Agency (IAEA), International Commission on Radiation Units and Measurements (ICRU), International Labour Organization, International Organization for Medical Physics (IOMP), International Radiation Protection Association (IRPA), International Society of Radiographers and Radiological Technologists, International Society of Radiology (ISR), Multidisciplinary European Low Dose Initiative (MELODI), National Council on Radiation Protection and Measurements (NCRP), Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA), International Platform for Social Sciences and Humanities in Ionising Radiation Research (SHARE), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), World Health Organization, World Nuclear Association (WNA). These organisations can play a crucial role in the review and revision of the System because they can provide valuable input based on their various missions and the views of their membership.

In 2021, ICRP published ideas on topics that might require careful consideration in the process to review and possibly revise the System (Clement *et al* 2021). The purpose of this paper was to stimulate the discussion within the international community. A digital workshop organised by ICRP from 14 October to 3 November 2021, offered a first platform for the international community to discuss the ideas described in that paper and present their own proposals to improve the System. The outcome of the workshop and the major take home messages are summarised in (Rühm *et al* 2022).

The aim of the paper by Clement *et al* was '*to encourage discussions on which areas of the System might gain the greatest benefit from review, and to initiate collaborative efforts*' (Clement *et al* 2021). It did not, however, discuss any scientific efforts that would be useful to improve the System. To fill this gap, an accompanying paper was recently published with the aim '*to complement the research priorities promoted by other relevant international organisations, with the specificity of placing them in the perspective of the evolution of the System of Radiological Protection*' (Laurier *et al* 2021).

To offer the international community a platform to comment on that paper, ICRP organised an international workshop in conjunction with the European Radiation Protection Week in Estoril, Portugal, on 10 October 2022. The workshop focused on areas of research to support radiological protection, specifically considering the evolution of the ICRP System of Radiological Protection, aiming to complement research priorities promoted by other international organisations. It was an opportunity for international organisations to share their views on what they considered the most important research topic(s) in radiological protection on the medium and long term. The workshop included a series of short remarks followed by a panel discussion allowing for audience interaction to encourage additional views and feedback.

Altogether, about 150 individuals participated in the workshop. After the workshop, 16 out of the 30 organisations in formal relations with ICRP at that time provided written feedback. This publication summarises the views of those organisations and finishes by summarising the major take home messages identified by ICRP.

2. Research gaps identified by ICRP

In the recent paper by Laurier and co-workers, various areas of research were identified that—if successfully addressed—have the potential to support the current review of the System of Radiological Protection. According to the authors, the research needs identified require a '*wide range of disciplines, some overlapping, including but not limited to artificial intelligence, communication science, dosimetry, ecology, epidemiology, ethics, medical imaging and radiotherapy, modelling, radiobiology, social sciences, technology development, toxicology and uncertainty an*alysis'. Three main areas of research were identified including (a) research to support radiation risk assessment, (b) research to support dosimetry, and (c) research to support the application/implementation of the System of Radiological Protection. Typically, the discussed research topics were categorised either as requiring short/mid-term research (which could still support ICRP's current efforts to review the next general recommendations on the System of Radiological Protection) or longer-term research (beyond about 10 years) (Laurier *et al* 2021).

2.1. Research to support radiation risk assessment

In the short and mid-term, further research could for example help to clarify whether the current classification of radiation health effects into tissue reactions and stochastic effects is still useful or would require refinement. Calculation of radiation detriment would benefit from improved cancer risk models and tissue weighting factors, a clarification of dose-rate effects and cancer, and an update of non-radiation factors such as lethality, quality of life, and years of life lost, all used in detriment calculation. Improved knowledge on how and to what extent ionising radiation may induce diseases of the circulatory system including the corresponding shape of the dose–response curve would allow estimation of the potential impact of those diseases on radiation detriment. Further research on the health effects due to *in utero* exposure and on heritable effects of radiation on offspring and next generations, complemented by an overall uncertainty analysis, would further enhance calculation of radiation-related detriment. While the current System of Radiological Protection is largely developed for reference populations, further research on individual response of humans to radiation may inform protection approaches which could include at least some elements of stratification or individualisation. Finally, significant gaps were identified in the knowledge on the effects of ionising radiation on non-human biota.

In the longer term, fundamental research may for example address health effects of combined exposures, for example ionising radiation and chemicals, etc. This would support development of a holistic approach of radiological protection taking into account risks from exposure to ionising radiation and other stressors.

2.2. Research to support dosimetry

In the short and medium term, research on dosimetry could enhance current knowledge on relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (w_R) all used to account for the fact that—given the same absorbed dose—exposure to different radiation qualities may result in different biological effects. Development of refined dosimetric quantities, in particular for medical applications, may support improved radiological protection of patients. Development of new approaches that consider both stochastic effects and tissue reactions, situation-specific conditions such as thyroid blocking or contaminated wounds, and individual characteristics (such as iodine deficient diet in affected regions, for example) may improve emergency dosimetry.

In the long term, definition of and research on dosimetric targets in organs and tissues may for example strengthen the methodology for the protection of the environment, while development of more refined biokinetic models for incorporated radionuclides and radioactive substances may be needed to describe the transfer of radionuclides to the foetus from the mother, and to the new-born, infant and toddler through maternal milk.

2.3. Research to support the application/implementation of the System of Radiological Protection

In many areas, development of radiation technologies and their applications is an extremely dynamic process and requires careful and continuous analyses of any potential implications for radiological protection. Areas identified by Laurier *et al* (2021) include for example the medical use of ionising radiation including the development of FLASH and other new beam delivery modalities in radiation therapy, or the use of cumulative imaging examinations or repeated fluoroscopic-guided interventional procedures. In veterinary practice, individual animals are increasingly treated by medical procedures originally developed for human use, even if those procedures are not medically but, for example, only economically indicated. In such cases, further research should inform aspects of justification, optimisation, and dose limitation. Increasing efforts in the development of new technologies that facilitate reuse and recycle of naturally occurring radioactive material (NORM) and support reaching global sustainability may have implications for radiological protection. Finally, exposures from natural sources of ionising radiation may change with advances in technical developments (e.g. exposures to indoor radon due to changes in building technologies (ventilation, construction materials) required in response to climate change or reduction in energy consumption; exposures to cosmic radiation due to increasing air and space travel).

An improved and more holistic approach to ecosystem protection was identified in (Laurier *et al* 2021) as another field of research that might enhance the System. For example, research is needed to understand how ionising radiation exposure influences biodiversity and ecosystem services, including a broad range of natural environments as well as environments impacted and shaped by human activities.

Research is also needed that broadly covers the many types of social, ethical, communication, and technology assessment research that are necessary for a successful development, application and communication of the System. Relevant aspects include implications of artificial intelligence (AI) to radiological protection practice, social science research on perception and understanding of radiation and its use, and mechanisms for stakeholder involvement and communication science. Additional ethical considerations are needed for example with respect to specific individuals such as research subjects, medical (including veterinary) practitioners and patients. Psychological consequences of exposure to ionising radiation should also be considered. Finally, the impact of individual, organisational, and societal (cultural) actions, attitudes, and behaviours, including economics and response to stressful or unknown situations, on radiological protection should be investigated applying methods from behavioural science (Laurier *et al* 2021).

3. Feedback from international organisations

3.1. IAEA (Miroslav Pinak)

The IAEA has statutory obligation for establishing or adopting standards of safety for protection of health and minimisation of danger to life and property, and for providing the application of these standards (www.iaea.org). The current General Safety Requirements on Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, GSR Part 3 (IAEA 2014), is to the extent applicable, built on the System of Radiological Protection as is described in ICRP *Publication 103* (ICRP 2007) and in other supplementary ICRP recommendations. IAEA highly values the work of ICRP, in particular its recommendations and guidance in all aspects of radiological protection which represent an extremely valuable source of information. This is recognised in IAEA safety standards with explicit reference to particular ICRP recommendations.

As IAEA safety standards are subject to ongoing critical evaluation and review in the IAEA member states, it is important to maintain an open mind on their appropriateness and adequacy in the future. In particular, if new scientific evidence becomes available, it may be necessary to review the scientific basis for the IAEA safety standards. In this context the IAEA fully supports ICRP in its role to advance for the public benefit through improved radiological protection, in particular by providing recommendations and guidance based on the latest scientific evidence. The IAEA therefore not only fully supports the ICRP initiative to critically review the fitness for purpose of the current System of Radiological Protection in the light of the latest scientific evidence, but also would like to assist and collaborate with ICRP in fulfilling its important and valued role sharing a common objective: protecting people and the environment against the harmful effects of radiation exposure without unduly limiting the individual or societal benefits of activities involving radiation.

In relation to the current ICRP initiative to conduct a critical review on the fitness for purpose of the current System, two clear messages from the IAEA were communicated to ICRP: the first one is the agreement with ICRP's view that the System is robust, fit for purpose and has performed well. And the second one is that there is a need for stability of the System while supporting its clarity and consistency.

Concerning areas as presented during the workshop on 'Review and Revision of the System of Radiological Protection: A Focus on Research Priorities', the IAEA expressed its view in relation to the following subjects:

- Effects and risks in biota and ecosystems (ICRP Committee 1): from a practical perspective, the IAEA urges consideration of how effects and risks in biota and ecosystems will be incorporated into assessments. The IAEA questions the value of introducing complexity into assessments, especially given the uncertainties involved. Introducing further complexity could slow down the adoption of the System.
- Exposure situations and categories of exposure (ICRP Committee 4): introducing further complexity (e.g. creating a new exposure category for the environment) could slow down the adoption of the System. Protection of the environment needs to remain integrated with the System, but this can be achieved without creating a new category of exposure. The IAEA supports every reasonable attempt to clarify and simplify the System. Clarification is particularly welcome in relation to the existing exposure situations.

3.2. IOMP (John Damilakis)

The IOMP was founded in 1963. Currently it represents almost 90 national member organisations (NMOs) plus two affiliate organisations, six regional organisations, and corporate members. The mission of IOMP is '*to advance medical physics practice worldwide by disseminating scientific and technical information, fostering the educational and professional development of medical physicists, and promoting the highest quality medical services for patients. The objectives of the IOMP are to organize international cooperation in medical physics and allied subjects; to contribute to the advancement of medical physics in all its aspects, especially in developing countries; and to encourage and advise on the formation of national organizations of medical physics in those countries which lack such organizations*' (www.iomp.org).

Among the research topics discussed by ICRP in Laurier *et al* (2021), IOMP considers the following topics especially relevant:

- Patient dose optimisation based on personalised (patient-specific and equipment-specific) dosimetry and a combination of objective and subjective image quality assessment (QA): this topic is mainly related to diagnostic radiology x-ray methods and to fluoroscopically guided procedures.
- Use of AI for dose prediction, medical image quality improvement, and development of decision support systems: obviously, this is applicable to all fields and specialities including diagnostic radiology, interventional radiology, nuclear medicine, and radiotherapy.
- Dose assessment and optimisation in image-guided radiotherapy (cone beam computed tomography (CBCT)): CBCT is used widely in radiotherapy, and many hospitals apply the 'one size fits all' principle. Typically, only protocols for adults are available, and paediatric protocols and dose reduction tools should be developed.
- Virtual clinical trials in medical imaging: to assess imaging technologies one mainly relies on phantoms. However, phantom results cannot predict clinical efficacy. Preliminary results show that virtual clinical trials in medical imaging are feasible and should therefore be developed.

3.3. IRPA (Claire-Louise Chapple)

The IRPA is an association of radiation protection (RP) professionals joining through national and regional RP societies. Currently there are 53 associate societies from 68 countries. IRPA promotes '*the worldwide enhancement of professional competence, radiation protection culture, and practice by providing benchmarks of good practice, and encouraging the application of the highest standards of professional conduct, skills, and knowledge for the benefit of individuals and society*' (www.irpa.net).

IRPA has had a long-standing interest and active involvement in consideration of the system of protection (Coates and Czarwinski 2018). More recently, IRPA has been collating feedback from associate societies in countries across the world, on the proposed revision of the ICRP System, including priorities for research. There it has been commented that research should be prioritised in two ways; firstly, according to the highest exposures and, secondly, in relation to research that underpins the revision process as a whole.

In relation to the first of these, research in the medical field is a high priority for practitioners in many countries, particularly in relation to new technologies, including radiotherapy techniques such as proton therapy, FLASH and targeted functional radiotherapy plus development and use of new radionuclide imaging and therapy techniques. The development of individual dose and risk estimation and the application of this to patient care are also important topics for research.

In relation to broader issues underpinning the revision of the System, the key priority that has been fed back relates to how the System should be applied at low doses and low dose rates. Continued research into low dose and dose rate effects is encouraged, together with improved understanding of radiation risk as part of an all-hazards approach, and alongside costs and benefits. There is also a desire to see radiological protection rooted in an ethical framework, with a strong focus on communication and sustainability, and research in these areas is considered a priority.

The final area that has been mentioned by multiple regional radiological protection societies is continued research into non-cancer effects, including radiation effects on the eye and cardiovascular system, again this is seen as particularly important at low doses and in the medical sector.

3.4. NEA (Christopher Mogg)

The NEA operates within the framework of the OECD. It is an intergovernmental agency that facilitates co-operation among countries with advanced nuclear technology infrastructures to seek excellence in nuclear safety, technology, science, environment and law. The NEA objective is '*to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes*' (www.oecd-nea.org).

The NEA has published a report setting out its 'Initial Views on the Review and Revision of the System of Radiological Protection' (Nuclear Energy Agency (NEA) 2023). The report, which has been prepared by the NEA's Expert Group on International Recommendations (EGIR) operating under the Committee on Radiological Protection and Public Health, provides a collective view of member countries on the topics that should be targeted for improvement in the ICRP's review and revision of the System. As a follow-up to the publication of the report, the EGIR will carry out further research and investigation of some of the topics highlighted in the report to assess the current application and implementation and identify areas for improvement to be shared with ICRP, including the research topics as set out below.

The NEA supports ICRP's decision to review and refresh the System of Radiological Protection. The general view is that the current System has contributed substantially to the provision of radiation safety and protection over many years and the proposed review should focus on delivering continuous improvement rather than a significant overhaul. The NEA has identified several areas, including optimisation, environmental protection, radiological detriment and risk, and exposure situations, which should be prioritised for further review and research in order to deliver such improvements. Within this is a key research priority to review how non-radiological risks are better integrated into the System. For example, in the context of optimisation there is a need to develop the understanding of how wider social, environmental and economic impacts are accounted for and balanced against radiological risks. Continued integration of environmental protection into the system is another key research theme, including the links with the UN Sustainable Development Goals (SDGs), and more specific issues, such as how protection of environment is addressed in emergency exposure situations.

There is also a need to investigate how the System will need to evolve and adapt to deal with future changes, such as societal changes, new technologies, wide-scale decommissioning and changing risk profiles, including how the system applies in the context of hostile events. Climate change adaptation, sustainability and ecosystem services are key issues that need to be better understood to ensure the System remains resilient and fit for purpose in the coming decades. Underpinning all of the research priorities is the fundamental need to ensure that any changes to the current system result in a net benefit for stakeholders. This includes reviewing how the System is applied and implemented, with a detailed understanding that the recommendations put forward by ICRP work effectively in practice.

3.5. WNA (Peter Bryant)

The WNA is the international organisation that represents the global nuclear industry. This includes nuclear energy operators, mining and fuel fabrication companies and reactor vendors. As such WNA views are very much from the nuclear industry and practitioners' point of view. The association's mission is '*to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate*' (www.world-nuclear.org).

WNA's primary view is that any research should be outcome focused. Namely answering the question: 'Does this improve protection of people or the environment from ionising radiation?'

The nuclear industry for many years demonstrated its capability of controlling and reducing exposures. While there are variations across the individual elements within the nuclear fuel cycle, through optimisation of exposures the industry has reached a point where the average worker doses are around 1 mSv y^{-1}. This is within the variability of natural background radiation.

However, as the exposures across the industry continue to decline, there is now evidence that the application of the optimisation principle (i.e. that 'the likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors' (ICRP *Publication 103*)—As Low As Reasonably Achievable (ALARA)) and the system of protection in the purest sense can result in a disproportionate outcome in terms of introducing wider non-radiological hazards (Bryant *et al* 2017), and/or use of resources whether that is physical, financial or human (Coates 2017) (Bryant 2021). Therefore, the priority for the nuclear industry is into research that:

- Supports the integration of sustainability and a holistic 'All Hazards' approach into the System including explicit consideration of the environment, and
- Improves communication of radiation risk to the public and wider stakeholders to allow them to make informed decisions on 'What is Safe'.

WNA encourages researchers and ICRP, to strengthen their engagement with the nuclear industry and practitioners in support of this research and development, to help ensure this maintains a view of being outcome focused and usable for the practitioners.

4. Feedback from European and regional organisations

4.1. EAN (Pascal Croüail, Fernand Vermeersch, Julie Morgan, Nicolas Stritt, Sylvain Andresz)

The EAN was established in 1996 by the EC and became self-sustainable in 2005. Its objectives are '*to promote a wider and more uniform implementation of the ALARA principle*' (i.e. to keep the likelihood of incurring exposure, the number of people exposed, and the magnitude of their doses ALARA, considering economic and societal factors) '*for the management of public, patient and worker's exposures, to provide a focus and a mechanism for the exchange and dissemination of information from practical ALARA experiences and good radiation protection practice, and to identify and investigate topical issues of common interest to further improve the implementation of ALARA*' (www.eu-alara.net).

The EAN reflected on its activities in the current landscape of radiological protection and developed its strategic agenda for the coming years. The following key ALARA themes are included in the strategic agenda for 2021–2026:

- In the medical field, attention is given to interventional radiology, new imaging techniques and the production and safe use of new radiopharmaceuticals, with special attention to exposure situations involving alpha emitters. Also, the further development of new techniques, such as vector radiotherapy and theragnostics is considered important.
- In the nuclear industry, in research and in the medical field, EAN focuses on a further harmonisation of practices in the implementation of the ALARA principle.
- Existing exposure situations and the application of the ALARA principle in the prevailing circumstances is still challenging and needs further focus.
- Also identified is the need to assure knowledge and skills in the radiological protection community to implement the ALARA principle in all exposure situations. This requires an ongoing focus on maintaining and expanding skills and competencies, through radiological protection and ALARA education and training.
- In the above themes attention is given to the practical implementation of the ALARA principle in the context of an 'all hazards' approach in prevention and exposure management.

Consequently, the EAN identified particular interests in the following topics and ICRP Task Groups (TGs), in line with EAN's strategic agenda:

- ICRP TG114 reasonableness and tolerability in the System of Radiological Protection
- ICRP TG124 application of the principle of justification
- ICRP C4 exposure situations and categories of exposure (including the environment) (with C3) e.g. TG 127
- ICRP C4 optimisation including constraints and reference levels (once work on reasonableness is further developed) (with C3).

The EAN is prepared to further support ICRP in its review of the current System, in particular in the field of the practical implementation of the optimisation principle, reasonableness and acceptability. EAN is ready to provide support in the tuning of the next recommendations, based on the data and experience from the field. This can be done by activating the tools at EAN disposal such as working groups, workshops, surveys, newsletters on specific topics proposed by, or in coordination with, ICRP. All in all, a privileged connection with ICRP Committee 4 is appreciated and will be continued.

4.2. EURAMED (Joana Santos)

The EURAMED represents a consortium of associations involved in the application of ionising radiation in medicine, namely the EANM, the EFOMP, the European Federation of Radiographer Societies, the ESR, and the European Society for Radiotherapy and Oncology. EURAMED aims to improve medical care through sustainable research efforts in medical radiological protection, to identify common research areas defined in a common strategic research agenda (SRA), to serve as a platform for medical radiological protection research at European level, and to develop an aligned approach and response to European research calls. Since 1 October 2017 EURAMED is a non-profit organisation registered in Austria (www.euramed.eu).

EURAMED promotes research and teaching and by publishing scientific and professional information, especially a SRA in the field of medical radiological protection research (https://link.springer.com/article/10.1007/s13244-016-0538-x), thereby increasing the science base in medical radiological protection. EURAMED is leading European research activities in medical radiological protection and harmonising clinical practice to advance the European radiological protection safety culture in medicine.

Through the SRA, several research topics considered necessary and most urgent for effective medical care and efficient in terms of RP were summarised in five main themes:

(1) Measurement and quantification in the field of medical applications of ionising radiation.
(2) Normal tissue reactions, radiation-induced morbidity, and long-term health problems.
(3) Optimisation of radiation exposure and harmonisation of practices.
(4) Justification of the use of ionising radiation in medical practice.
(5) Infrastructures for quality assurance.

EURAMED is also involved in several projects such as CONCERT (the European Joint Programme for the Integration of Radiation Protection Research) and MEDIRAD (Implications of Medical Low Dose Radiation Exposure). Based on MEDIRAD's research findings the future research topics were defined:

- Conduct further research into adverse effects of ionising radiation on healthy tissues;
- Promote an European Union (EU)-wide research strategy to use AI for optimising protection in radiation oncology;
- Develop biologically-based models to evaluate radiation-induced disease risk;
- Conduct large-scale clinical epidemiological follow-up of patients to assess late health effects of radiation;
- Investigate new and optimise existing medical imaging procedures to improve benefit/risk ratios and personalised approaches.

4.3. European Association of National Metrology Institutes (Oliver Hupe)

The European Association of National Metrology Institutes ('EURAMET') is the regional metrology organisation of Europe with 37 member countries. It promotes European co-operation in the field of metrology for the development and application of measurement science and standards, and a globally recognised measurement infrastructure (www.euramet.org).

European Metrology Network (EMN) for RP aims to act as a single point of contact covering the metrological requirements related to radiological protection. To enable quality assurance in the area, the network fosters a harmonised, sustainable, coordinated and smartly specialised metrology infrastructure to underpin the needs expressed by stakeholders and in the European regulations for radiological protection. A special focus of the EMN will be the cooperation with regulators to actively contribute to the development of new and to the revision of existing standards. A key objective is to provide equal quality of metrology services and activities in radiological protection all over Europe. This can only be achieved if each member state applies equal metrological based QA for all radiological protection issues (www.euramet.org/european-metrology-networks/radiation-protection).

For the establishment of the EMN, the supporting project 19NET03 supportBSS has received funding from the European Metrology Programme for Innovation and Research co-financed by the participating states and from the EU's Horizon 2020 research and innovation programme.

The EMN for RP has identified the following needs:

- To include the aspects of metrology and quality assurance as they are established in the international SI system of units: for this, it is important to maintain a close contact to the ICRU and the Consultative Committee for Ionizing Radiation of the Bureau International des Poids et Mesures. Metrology (especially quality-assured, traceable measurements) is the base of trustworthiness of measured data.
- To harmonise the implementation of regulation: for example, radiation doses are measured below the protective clothing in some countries and above in others. Therefore, dose values in national dose registers are not comparable. Pulsed radiation and laser-induced radiation are handled differently in different countries, which makes it difficult for industry to develop suitable dosimeters. The conversion factor for radon has developed into a most 'disharmonised' subject. The implementation of the proposed new operational quantities (ICRU 2020) could lead to a likewise confusion.
- To support education and training, which is the best measure to promote radiological protection: reliable and sustainable access to training at all levels of expertise is needed. This could be achieved through dedicated training centres or at least coordinated training activities.
- To underpin emergency preparedness, during and especially after nuclear events of any kind.
- To make research resources available: this applies especially in new areas and new technologies, e.g. online-dosimetry through computational methods, detection of UV radiation to identify alpha particle contamination, as well as future challenges and opportunities of digitalisation.
- To support innovative technological developments, which, e.g. include new radiation exposure scenarios: measures to respond to these new needs include increasingly restrictive exposure limits, the introduction of reference values for activity concentration, and enhanced quality assurance requirements for legal dose assessment. To enable quality assurance in the area, a harmonised, sustainable, coordinated and smartly specialised metrology infrastructure is needed to underpin the needs expressed by stakeholders and in the European regulations for radiological protection.
- To ensure the applicability of the ICRP recommendations in practice.

4.4. EANM (Michael Lassmann)

The EANM was founded in 1985 as a merger between the Society of Nuclear Medicine Europe and the European Nuclear Medicine Society. The EANM's vision is '*to optimise and advance science and education in nuclear medicine for the benefit of public health and humanity within the concept of personalised healthcare …*'. Its goal is to be a '*platform for the dissemination and discussion of the latest results in the field of nuclear medicine, including multimodality imaging and related subjects. It fosters and coordinates the mutual exchange of knowledge relating to the diagnosis, treatment and prevention of diseases …*' (www.eanm.org). EANM has identified the following topics to be of high relevance for nuclear medicine.

- Dose and risk coefficients for radiopharmaceutical therapy: dose and risk coefficients are needed for further personalising radiopharmaceutical therapies. Because therapies with radiopharmaceuticals labelled with alpha particles such as [^{225}Ac]Ac–prostate specific membrane antigen (PSMA) will become more and more available in the near future (Kratochwil *et al* 2020) research on the underlying biological mechanisms and the corresponding RBE related to those radiopharmaceuticals is needed. This compares to results on radiopharmaceuticals labelled with beta-emitters. In this regard a first step concerning was already taken by ICRP with *Publication 140* (ICRP 2019). However, as a follow-up more details on methodology as well as radiobiology should be considered (Konijnenberg *et al* 2021, Pouget *et al* 2022)
- Justification in medicine: for all nuclear medicine procedures, ICRP should develop a clear position on justification in the area of very low doses, weighing obvious benefits against very hypothetical risks in the 1 mSv dose range for all age groups.
- Update of radiation doses from radiopharmaceuticals: in 2015, ICRP has published its latest compendium on radiation doses to patients from radiopharmaceuticals (ICRP 2015a). As the tissue weighting factors in this compendium are still based on ICRP Publication 60 (ICRP 1991), the EANM considers it important that ICRP publishes a report replacing this compendium. Such an update is urgently needed for daily practice in diagnostic nuclear medicine imaging.

4.5. EFOMP (Lorenzo Nicola Mazzoni)

The EFOMP was founded in 1980 to serve as an umbrella organisation for (as of September 2022) 35 NMOs. The mission of EFOMP is '*to harmonize and advance medical physics both in its professional clinical and scientific expression throughout Europe, and to strengthen and make more effective the activities of the NMOs by bringing about and maintaining systematic exchange of professional and scientific information, by the formulation of common policies, and by promoting education and training programmes*' (www.efomp.org).

For EFOMP, one of the key points for the successful development of a modern discipline lies in the link between university education, research, and the professional world. In fact, education, research and professional activities are three interconnected pillars, which need a common harmonious development. This is particularly challenging, because radiological protection embraces very different fields of application, such as energy production, medicine, biology, environment, etc. It is necessary to reinforce research and training in radiological protection in all these fields, in particular through the active participation of students and young professionals. For this purpose, ICRP has for example initiated their mentorship programme, and for similar purposes EFOMP has recently established a special interest group dedicated to early career medical physicists (Marcu *et al* 2022). Joint actions may be promoted in the future.

Many of the research points raised in a (Laurier *et al* 2021) are important to EFOMP, and in particular the following topics:

- Further research is needed to better understand tissue response and establish consequent protective actions, with particular attention to non-cancer effects (for example effects on the cardio-vascular system).
- The importance of uncertainties in both dosimetric monitoring and risk estimates at low dose and low dose rate requires further research, also to provide practical suggestions on how to use dose constraints. For example, what is the reasonable dose estimation accuracy for exposed workers when the annual effective dose is less than 1 mSv y^{-1}? Accurate low dose estimates can be complex and expensive, especially if performed on a large number of workers. On the other hand, an accurate monitoring is necessary to draw consistent conclusions when exposures are very low.
- EFOMP agrees with ICRP that '*research and collation of information is continuously required in relation to the best use of ionising radiation and radioactive materials in medical diagnosis and treatment*' (Laurier *et al* 2021). This is particularly important for new diagnostic and treatment modalities, for example FLASH radiotherapy, hybrid systems like magnetic resonance imaging guided linear accelerators (MR-LINACs), and novel tracers in nuclear medicine.
- It is also fundamental to promote individual optimisation in medical exposures, with specific attention to patients with cumulative imaging examinations (Rehani and Nacouzi 2020, Frija *et al* 2021), also developing and testing the clinical effectiveness of new strategies based on AI (Samei *et al* 2018, Doria *et al* 2021).

4.6. ENISS (Tapani Eurajoki)

ENISS was established in 2005. Currently it represents nuclear installation licence holders from 16 European countries with nuclear power plant (NPP) units, fuel reprocessing plants or large waste storage facilities. The missions and strategic objectives of ENISS include '*to develop common views and positions on the evolutions of the nuclear safety standards, to interact appropriately with the regulators and the key stakeholders to ensure that the licensees' positions, through ENISS, are effectively given due consideration, and to maintain an efficient information exchange platform between ENISS members with respect to nuclear safety matters*' (www.eniss.eu).

ENISS represents the European nuclear industry, and hence one of the 'end users' of the radiological protection system. ENISS applies the System at the 'floor level' in their facilities for the protection of workers and the public. In the nuclear industry, the typical average annual effective dose rates are low or very low, i.e. on average below 1 mSv y^{-1} for radiation workers and below 1 μSv y^{-1} for members of the public, respectively.

A significant issue to be borne in mind is that the uncertainties of our knowledge on the effects associated with those dose rates are large, and hence it is a relevant research topic. Many of the research topics mentioned by ICRP are relevant *per se* to enhance the understanding of the effects of radiation. However, from the nuclear industry point of view it is also important to appreciate that there is a long path from scientific research to practical implementation of radiological protection. Considering the low levels of dose rates mentioned above, a graded approach and an impact assessment of any changes that might be proposed to the System are of utmost importance. In other words, should there any changes be introduced to the System, their net effects should result in an improvement of safety, considering the efforts that are needed to implement those changes.

Optimisation of radiological protection is a good example for that. During the last decades optimisation has resulted in a significant reduction of both collective and individual occupational doses, but at the same time optimisation of protection has tended to be interpreted as dose minimisation. One may ask, whether the dose reduction has gone even too far, beyond the optimum.

Regarding some specific topics presented for future research by Laurier *et al* (2021), some of them do not touch nuclear industry, and some touch them only to a limited extent, e.g. radiological protection of non-human biota. As the discharges from the normal operation of nuclear facilities result in minimal doses for the public, they are not likely to result in undue harm to the other biota, and therefore, according to the graded approach, they should not require excessive attention (analysis, calculations, reporting) from the nuclear industry.

4.7. European Partnership for Radiation Protection Research (PIANOFORTE) (Liz Ainsbury)

PIANOFORTE (www.pianoforte-partnership.eu) is the European Partnership for Radiation Protection Research, which has the simple overarching aim of improving radiological protection of members of the public, workers, patients and the environment. The project officially started in June 2022, will run for 5–7 years, and is led by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France, with contributions from 58 partners in 22 countries of the EU plus Norway and the United Kingdom. The budget is 46 million Euros, the vast majority of which will be dedicated to three open research calls. The main objective of PIANOFORTE is to support scientific research in the field of radiological protection.

The priorities within PIANOFORTE will be based on the Joint Road Map (JRM) of the European Joint Programme for the Integration of Radiation Protection Research (CONCERT) that preceded PIANOFORTE (Impens and Salomaa 2020). CONCERT did a lot of work on prioritisation for research and was successful to a certain extent. However, the process was, and remains, very challenging. Genuine agreement across the European research platforms and stakeholders is never going to be easy. Thus, engagement between ICRP and all PIANOFORTE partners in relation to this important question is warmly welcomed. Furthermore, input from the partners including the European research platforms and national programme owners or managers is encouraged, as is the widest possible group of stakeholders from across society. The prioritisation process will be ongoing as the calls are launched, but the priorities will include at least to some extent the common topics of medical applications and low dose risk estimation, as well as a wider focus on research infrastructure and training. PIANOFORTE's ambition is that the funded projects will advance scientific understanding in a way that will feed directly into the update of the System.

Going forward, in addition to research, PIANOFORTE seeks to, and encourages ICRP to:

- Ensure genuine <u>involvement</u> of the widest possible set of scientific, industrial and scientific stakeholders, including consideration of equality, diversity and inclusion. It is well documented that the more diverse the group of experts who seek to address a problem, the better the solution serves our diverse society;
- Support education and training for early career researchers, to help attract and maintain expertise in radiological protection research;
- Operate in accordance with the Green Deal, and consider the UN SDGs;
- Act according to the FAIR principles, so that everything we do within the community is findable, accessible, interoperable and reusable, as far as possible.

PIANOFORTE recognises and supports the activities of ICRP in stakeholder engagement and education and training, including running open workshops and the mentee programme, but believes ICRP could go further in all of the above areas, to help make the process of the review of the System and implementation of any changes as fair and equitable as possible.

4.8. NERIS

The NERIS welcomes the efforts of ICRP to review research in support of radiological protection. What might be missing among the current ICRP research priorities, however, is clearer guidance on how to improve the practical implementation of RP in emergency exposure situations especially under 'special circumstances' like war, armed conflict or significant natural disaster situations. Research in this area should also address the topics 'radiation protection in case of nuclear explosions (atomic bombs)' and 'radiation protection in war situations/armed conflicts' (one example is the potentially limited applicability of evacuation that may require alternative protection strategies).

Recently, NERIS has concluded that war situations have not sufficiently been considered in RP and pose specific challenges. In this context, the following research topics have been identified:

- Preparedness and response: detailed study of the lessons identified for radiological protection during the war in Ukraine could lead to a better preparedness and response. This should include an investigation of how those lessons can be applied in other situations (e.g. natural disasters);
- Nuclear and radiological warfare: the threat of nuclear and/or radiological warfare calls for impact analyses of such scenarios. Many such impact studies are based on historical work. More realistic assessments could be made, including identification of improved source terms (for example, types of radionuclides, relevant physicochemical forms, release heights, post-deposition behaviour) and advanced atmospheric dispersion and transport calculations making use of the numerical weather data available nowadays. Such calculations could inform how to develop generic and specific guidelines on protecting people affected by nuclear fallout and allow estimations of the impact of fallout on the food chain;
- Application of radiological protection principles: in this context, the additional complexity implicated in a war situation and its threats (e.g. the potentially limited applicability of evacuation) should be explored;

- Emergency preparedness, planning and response in a wider framework of civil defence: a range of different emergency and recovery situations could arise, as nuclear weapons could range widely from the biggest to small tactical nuclear or radiological weapons primarily creating fear and making land areas inaccessible. Very different contaminants could be involved requiring different planning and mitigation approaches which should be analysed and described;
- Radiological mapping: depending on the situation in Ukraine, support could be organised to assess the radiological situation. This could include, for example, the search for (lost) radioactive sources and re-mapping of parts of contaminated areas around the Chornobyl NPP applying and comparing different and novel techniques and strategies, investigating the reproducibility of such measurements and assessing the (change in) impact on human and non-human biota. Important parameters may be deduced that would be valuable also in other situations where data is sparse. This could be part of national and international initiatives in support of Ukraine.

'Sources and impact of uncertainties' is considered another research topic with high importance from a NERIS perspective, especially how uncertainties relate to the protection of people in an emergency.

In addition, there might be a need to improve general public understanding of all aspects of radiological protection, to allow people to make 'informed decisions' on how to optimally protect themselves in emergency exposure situations, especially under special circumstances such as war situations.

Also, in this context the principle of optimisation is important and would benefit from additional research efforts, specifically its practical implementation in emergency situations. NERIS supports clarification and simplification in this area. Furthermore, NERIS still sees some open questions when considering the practical application of the optimisation principle. For example, a key issue for improvement might be how to develop an optimisation process that considers other non-radiological risks, e.g. being caused by protective actions (loss of lives as result of evacuation in Fukushima) or by special circumstances (like armed conflicts). Finally, ICRP could provide more guidance on how to balance between positive effects of countermeasures and the broader health and socioeconomic impacts of these actions.

4.9. EURADOS (Rick Tanner)

The EURADOS is a sustainable network of 80 European institutions that is now over 40 years old. It exists to promote research and development and European cooperation in the field of radiation dosimetry (www.eurados.org). It does this via various working groups on harmonisation of individual dosimetry; environmental dosimetry; computational dosimetry; internal dosimetry; dosimetry for medical applications; retrospective dosimetry; and dosimetry in high energy fields. EURADOS first published its SRA in 2014 (Rühm *et al* 2016), and then updated it in 2020 (Harrison *et al* 2021). The current SRA includes five visions, which are subdivided into 18 challenges which cover 60 research lines. In addition, there are three overarching topics covering harmonisation and practice, education and training, and computational dosimetry.

From the perspective of EURADOS, the following points deserve special attention for the future RP system.

- The RP system can seem too complicated, and every effort possible should be made to simplify it. As an example, the new ICRU Report 95 operational quantities might be more consistent, but can hardly be called a simplification. EURADOS Report 2022-02 (https://eurados.sckcen.be/sites/eurados/files/uploads/Report-Publications/Reports/2022/EURADOS%20Report%202022-02.pdf) reviews the practical impacts of introducing the new operational quantities, but more work is required.
- The use of effective dose in medicine should be improved. There is sufficient progress in personalised dosimetry that would allow a patient-specific quantity, while recognising that more precise estimates of radiation risk are possible for an individual patient with more specific information.
- Similarly, for workers and the public we will surely evolve towards a personalisation of risks. There might not be enough data for this now, but it can be expected that this will come in the future. So, radiological protection should be adapted so that it can incorporate age, gender, dimensions etc in the risk evaluation. The dosimetry is advanced enough to take all this into account, and also the number of individualised phantoms is increasing.
- The division between tissue reactions and stochastic effects is fundamental in the system. However, there are tissue effects that do not seem to have a dose threshold. Does the system need to be changed for this?
- For the protection of the environment and non-human biota new research is needed. Can this system not be simplified, so that not so much effort is needed for non-human biota dosimetry?
- For the determination of radiation quality, there is progress in understanding via nano- and microdosimetry, and biophysical modelling (including advanced Monte Carlo codes for the fundamental chemico-physical effects of radiation on cells). This research should also be taken into account in the RP system.

- The ICRP should take into account new evolutions in computational dosimetry, online dosimetry, machine learning and AI.

4.10. FORO (Marcela G. Ermacora, João O. Martins)

FORO (Foro Iberoamericano de Organismos Reguladores Radiológicos y Nucleares) is an association of regulators from Argentina, Brazil, Chile, Colombia, Cuba, Spain, Mexico, Paraguay, Peru, Portugal and Uruguay. FORO was founded in 1997. The objectives of FORO do not include research activities, but as regulators FORO members depend on scientific results needed to base the development of regulations on sound scientific knowledge (www.foroiberam.org).

To give examples of relevant activities, FORO has recently finalised the SEVRRA II (radiotherapy risk assessment system) computer tool for intensity-modulated radiation therapy and diagnostic nuclear medicine practices, which will be available shortly on the FORO webpage (www.foroiberam.org). Furthermore, the FORO project on safety culture in organisations, facilities and activities is linked to the use of ionizing radiation sources, while the project on competences of personnel of regulatory bodies relates to medical and industrial applications. Results of these projects have been published in May and September 2022 together with the IAEA, in Spanish (IAEA TecDoc 1995, 2005). In 2023 the FORO plenary approved a revised action plan (FORO Revised Action Plan 2023), on which the following topics relevant for FORO are based:

- Reuse of NORMs for a sustainable economy.
- Safety culture aimed at strengthening the role that human and organisational factors play in reducing doses during activities with radiation sources, such as, in industrial gammagraphy, the import, export and transport of radiation sources for medical, industrial or research and training purposes, the management of radioactive waste derived from these activities.
- Licensing and control of proton therapy.
- Waste management (low and intermediate level waste and NORM).
- Protection of patients, workers and the public in medical and industrial practices.
- Training for regulators for improving the application of the System of Radiological Protection.

4.11. MELODI (Nathalie Impens)

The purpose of the MELODI Association is to define priority scientific goals and to encourage the implementation of research on health risks from low-dose and low-dose-rate radiation with the aim to improve radiological protection. In 2010 MELODI was founded as a registered association with 15 institutions as members. Currently, the number of members is 43 (https://melodi-online.eu/).

A robust understanding and quantification of human health risks is the fundamental basis of radiological protection; the system of protection for public, occupational, medical and emergency exposures flows from this basis. The SRA of MELODI identifies these priority goals and the specific resources, infrastructures and training capabilities needed to further develop low-dose risk research within a time frame of 20 years. MELODI statements aim to inform on priority topics for forthcoming EU and national calls and should facilitate setting priorities for both the EU and any subsequent European partnership calls.

The key priority for radiological protection research is to improve health risk estimates for low dose and dose-rate exposures encountered in occupational, medical and public/emergency situations. The approaches will need to be multidisciplinary and innovative, including where appropriate the application of AI and machine learning approaches. The integration of expertise outside the conventional fields of radiation research such as toxicology will widen the possibilities to integrate modern health research technologies in the assessment of health risk relevant to radiological protection. The priorities identified for the 2022–2027 period listed below take into account the feasibility and impact of the topic area (Melodi Road Map 2022) and the amount of related ongoing work on the topic.

MELODI priorities for the 2022–2027 period

The overall priority is as given in the Joint Platforms Roadmap, challenge A, *understanding and quantifying the health effects of radiation exposure* (Impens and Salomaa 2020). The following points provide more specific priorities within this overarching aim in light of recent developments:

- To understand the health effects of inhomogeneous exposures, various types of radiation including those from internal emitters, and differences between risks from acute and chronic exposures through the integration of experimental and epidemiological data applying biologically based risk models. To improve the understanding of the effects of intra-organ dose distribution through observations in patients exposed to inhomogeneous fields and experiments with organotypic tissue models.

- In relation to tissue reaction and stochastic health effects (cancer and other diseases): characterisation and quantification of variation in response and risk between population sub-groups/individuals due to host factors including genetic and epigenetic factors, sex, co-morbidities, environmental and lifestyle factors, co-exposures and the interactions between these depending on dose levels.
- To evaluate the risks of, and dose–response/dose-rate response relationships for, non-cancer diseases at low and intermediate dose levels (100–500 mGy and below): in particular cardiovascular, neurocognitive and immunological diseases.
- To define the processes contributing to cancer development in relevant target stem/progenitor cell populations after low-dose/low-dose-rate exposures; including for example the role of microenvironment, cell-to-cell interactions (as mentioned in ICRP *Publication 131* (ICRP 2015b)), the role of epigenetics, metabolic status, ageing, and immuno-senescence amongst others, in single and multiple stressor exposure situations.
- To identify, develop, validate and, where feasible, implement the use of biomarkers of exposure, and of biomarkers for early and late effects of cancer or/and non-cancer diseases and variation in susceptibility. The relationship between these radiation biomarkers and those emerging biomarkers of various pathophysiological processes and health outcomes needs to be considered and explored.
- To continue to refine risk estimates for cancers after low-dose and low-dose-rate exposures in occupational, medical and other epidemiological cohorts. Such quantitative risk estimations are required to inform judgements on risks from acute, chronic and inhomogeneous exposures, and will provide important input to the development of quantitative mechanistic risk models and adverse outcome pathways (AOPs), see below.
- To identify, explore and define AOPs for radiation-induced health effects, and determine if those operating at low doses and dose rates are the same as those operating at higher levels of exposure, and investigate when the triggering of an AOP is sufficient to disrupt normal homoeostasis and lead to pathologies.

The current and previous MELODI statements, providing information about short-term research priorities for specific calls, can be found on the MELODI website (https://melodi-online.eu). Research priorities for the medium and long-term are described in the CONCERT JRM.

MELODI encourages, where appropriate, (1) the use of archived biological materials from prior EU funded research, (2) the integration of experienced laboratory networks (such as e.g. Running the European Network of Biological and Retrospective Physical Dosimetry (www.reneb.net)), (3) the consolidation and use of important epidemiological studies (both radiological and non-radiological) where feasible, (4) the integration of expertise from outside the conventional fields of radiation research; (5) the use of shared infrastructures and (6) continued availability of targeted education and training opportunities (such as e.g. student mobility support) to share and spread technical skills.

4.12. Social sciences and humanities (SHARE) (Catrinel Turcanu, Susan Molyneux-Hodgson, Tanja Perko)

SHARE is the European platform for social science and humanities (SSH) research in ionising radiation, which connects over 40 partner institutes and researchers from different SSH disciplines. The mission of SHARE is '*to stimulate the integration of social sciences and humanities (SSH) in research, practice and policy related to ionizing radiation, including, for example: radiation protection, low dose risk, radioecology, emergency preparedness and response, dosimetry, medical applications, radioactive waste management, nuclear energy production, safety, NORM, and site remediation*' (www.ssh-share.eu/)

SHARE pointed out that the complexity of the System is not only due to the science involved and the related uncertainties, but also to the social, economic and political considerations that will always play a role. ICRP has '*acted at the interface between science and policies*' (Clement *et al* 2021) and appreciates that to continue to fulfil this role requires further expertise and competences from SSH. In this regard, the radiological protection community acknowledges that the 'science' in radiological protection has a socio-technical character. Four SSH insights of importance to the System are therefore worth highlighting.

- First, when discussing, researching, and planning for the future of radiological protection, it is critical to reflect not only on what research or policies are needed, but also on how that research is conducted and how policies will be decided upon. Early involvement of SSH disciplines in these processes—from problem formulation, through development of solutions, to implementation and evaluation—will allow the radiological protection community to identify and begin to address—in a timely manner—the ethical, social, and communication aspects that are important. Moreover, the SHARE SRA brings into focus the concept and practices of responsible research and innovation (RRI) (Owen *et al* 2021). Values linked to RRI include anticipation, inclusiveness, reflexivity and responsiveness to societal needs and concerns. Integrating these values into radiological protection research would render processes and outcomes more socially responsive and ethically sound.

- Second, attention to the advantages of transdisciplinarity is needed. ICRP already engages ethicists in some of the TGs. SHARE proffers that it must engage also with other SSH disciplines such as sociology, psychology, political sciences, history, and science and technology studies. There is also added value in making TGs transdisciplinary, such that insights from various disciplines, including SSH, as well as various stakeholders, including affected publics (e.g. workers, communities) can be reflected.
- Third, the need to balance the optimisation of radiological protection with the social and environmental dimensions is recognised (Laurier *et al* 2021). However, there is a need for greater attention to the inclusion of values of communities, patients, stakeholders, and consumers in the optimisation process. How can this be done? How are justification and optimisation applied in different contexts in an ethical way? SSH can provide evidence-based responses to these questions.
- Fourth, research priorities for SSH in the field of radiological protection have been identified in the SRA of the SHARE platform (SHARE 2020). These include topics such as attitudes, expectations, and behaviours with respect to radiological risks, and influencing factors, for different populations and in different exposure contexts; holistic approaches to radiological protection, integrating various disciplines and societal actors; stakeholder engagement models, tools, and practices; risk and health communication; and the development of radiological protection culture from a participatory perspective. These topics are partly recognised, but go beyond, the previous analysis of research needs by ICRP (Laurier *et al* 2021). The research lines identified in the SHARE SRA will continue to be relevant, even as societies are changing and new needs and opportunities emerge (such as the use of AI in medicine, which brings along not only opportunities, but also ethical and practical challenges), as well as new types of exposures or increased threats (for instance war, climate crisis). It is essential to research and gather evidence on how effective radiological protection practices are currently, and what the impacts will be of these wider evolutions in changing societies and a changing planet.

The radiological protection community must lift its head beyond narrow concerns with radiological risk perception and communication when thinking of the 'social' dimensions of radiological protection. A broad engagement with the full spectrum of relevant SSH research will be needed to ensure robust and resilient RP regimes. SHARE is willing to engage with ICRP on these issues and contribute to the important collective efforts towards a better radiological protection system and improved practices.

5. Discussion

In general, the work of ICRP and the value of the current System was explicitly acknowledged. The System was considered robust, applicable, and useful, and ICRP's role in international harmonisation of radiological protection was appreciated. At the same time, there was a consensus that the System must be based on up-to-date scientific findings and, at least for this reason, requires regular update. Consequently, the current process initiated by ICRP to review the System was broadly supported. Representatives of many organisations and institutions who participated in the workshop contributed to a lively discussion on research topics that could enhance radiological protection in the short, medium, and long term, supporting or complementing the topics mentioned by Laurier *et al* (2021).

5.1. Research topics in support of those mentioned by ICRP

Quite a few of the scientific topics summarised above were repeatedly mentioned and discussed by various participants, which may be an indication that those topics were considered of particular importance. For example, many participants identified research needs in the medical sector due the dynamic development of new technologies such as AI to be applied in medical imaging and radiotherapy. It was emphasised that this development requires careful monitoring to make sure that any implications for radiological protection are not overlooked. Particularly related to the needs of patients, many participants found scientific developments towards individualisation and personalisation in radiological protection useful involving for example personalised dosimetry, search for biomarkers to identify individual radio-sensitivity, and individualised risk estimates. While such studies already find it difficult to provide meaningful results when related to exposures to high doses and dose rates (radiotherapy), they are particularly challenging at lower exposure levels often encountered in occupational settings or in exposures of members of the public. Thus, continuous scientific efforts towards quantification of radiation risks at low doses and dose rates are still needed and were requested by many participants. For example, studies in radio-epidemiology were called for with a continuous follow-up of existing cohorts of individuals that had been exposed to ionising radiation, as well as biologically motivated studies including development of mechanistic models of diseases related to radiation exposure or AOPs.

Much of what has been said so far is related to the risk of cancer induction and mortality. In a way, this is justified due to the fact that the current ICRP System is in part motivated by the desire to keep the risk of solid cancers and leukaemia ALARA. However, because evidence is growing that other non-cancer diseases might also be of relevance, it was explicitly requested to also intensify research on additional health endpoints such as diseases of the circulatory system or cataracts.

Along these lines—when extending the System from just considering risks from cancer towards non-cancer risks—it appeared natural to many participants to go further and propose an 'all-hazards' or 'holistic' approach. For example, some participants requested to intensify research on non-radiological factors that might not necessarily directly be induced by ionising radiation, but nevertheless may deserve further consideration. This does not only include research on psychological effects after radiation exposure, but also risks from any prevailing chemicals or other co-stressors or risks other than radiation-related that may come along with any radiation exposure or radiological protection measures (for example, accidents during remediation actions of contaminated areas). And—to develop this narrative even further—any implications of such an 'all-hazards' approach on the System and its key principles (justification, optimisation of protection, and application of individual dose limits) should be assessed before any decision whether or not such an approach would be useful for radiological protection is drawn.

This thought leads to a more general and cross-cutting aspect. As the current System is generally considered robust and applicable, concerns were raised that any changes made—even if they would make the System more consistent with current scientific evidence—may not necessarily improve the System as a whole. Instead, concerns were expressed that this could make the System more complicated, more difficult to apply, and more difficult to communicate. Thus, it was emphasised that in the end any change should improve the overall protection of workers, members of the public, and the environment. Consequently, any proposed change should be preceded by a thorough impact assessment before a final decision on its implementation is made.

Finally, the need for continuous and even enhanced efforts in education and training activities was highlighted, in line with ICRP's recent Vancouver call for action (Rühm *et al* 2023). Other cross-cutting issues that might require further research included research on how to consider and possibly include uncertainties in the System, how to communicate the System having these uncertainties in mind and, more generally, how to further elaborate the role of the ethical foundation of the System. Clearly, answering these and similar questions goes beyond the remit of radiological protection specialists—that's why a systematic involvement of experts from the SSH area was called for.

5.2. Research topics in addition to those identified by ICRP

When the research gaps in Laurier *et al* (2021) were identified in 2019 and early 2020, the world was somewhat different than it is today. For example, the COVID-19 pandemic hit the world in 2020 due to the outbreak of a hitherto largely unknown virus—which has been and still is, like ionising radiation, invisible (a parallelism often highlighted in recent years). This forced countries all over the world to develop strategies that allowed balancing the risk of getting the disease with the wider economic impact of any countermeasures. Protective actions differed across countries highlighting the usefulness of international collaboration and harmonisation. Mental health and psychological impacts have become important issues, in addition to the direct and for quite some time unknown health consequences due to an infection with the corona virus. Any potential correlations between exposure and risk of infection were unknown, and scientific evidence slowly but continuously improved while the uncertainties involved have been and still are considerable. For a long time, it was unclear how to quantify those health effects, and how societies should best deal with any of the (unclear) risks. Moreover, it showed the importance of considering social, psychological, ethical and economic aspects, beyond the technical risk assessments. Many of these aspects have already been addressed in radiological protection, but some lessons learned from the pandemic may also be relevant for radiological protection. Consequently, various participants requested systematic research efforts to draw appropriate lessons from the COVID-19 pandemic to inform the current review of the System.

Furthermore, in 2021 the military conflict in Ukraine has led for the first time to active military actions close to an operating NPP. The shelling of the Zaporizhzhia NPP was an eye opener for many who thought that NPP emergencies only involve scenarios like those that had happened in Chornobyl or Fukushima. Thus, during the workshop it was requested that current protection strategies may need to be adapted to military scenarios, research on proper source terms might be needed, and how to apply the current radiological protection principles in such situations must be considered. For many, even the detonation of nuclear weapons has become a realistic scenario, and research on appropriate radiological protection measures in such cases was also called for.

On the technological end, many new technologies being currently developed or on the horizon require continuous monitoring for their implications for radiological protection. While the paper by Laurier *et al* (2021) already mentioned a number these developments (such as FLASH radiotherapy, AI, etc.), further examples were raised during the workshop including implications due to the new small modular reactor technology, detection of alpha emitters through their emission of UV light, development of individualised real-time dosimetry, and development of reference fields for new radiation sources or standards for new radionuclides used in nuclear medicine.

Although more than a century of research on the effects of ionising radiation to humans and the environment has already passed, various participants emphasised that further research is required to quantify radiation-related doses and effects on various levels of organisation (including on the tissue and population levels). New and burning research questions were discussed by the participants that—if answered—may enhance the System. For example, what is the effect of the exposure to ionising radiation on the human immune system? How will such exposure influence future generations? Are there further vulnerable groups in addition to those of young age or females who would require further attention? Related to this, would studies focused on those patients with diseases that might influence specific biokinetic features improve their radiological protection during radiotherapy? Will it be worthwhile considering the effects of stressors other than ionising radiation and will this influence the way radiological protection is handled? Will the AOP approach provide further insight in the effects of low doses and dose rates? And to what extent will further research on the ecosystem level (including for example comparison between the impacts on wildlife and experimental animals) improve the protection of the environment?

On a broader perspective, the question was raised how radiation research and radiological protection can contribute towards the 17 SDGs announced by the UN in 2015, to support a sustainable development of the world by 2030 (UN General Assembly 2015). For example, the question was raised how much resources should be spent to reduce radiation doses and dose rates that are already low, i.e., of the order of natural dose and dose rate levels or even below. Again, this touches one of the key principles of the System—the question of reasonableness and optimisation. Another question raised was whether radiological protection can contribute to fight climate change. Such aspects were, for example, not directly mentioned in the paper by Laurier *et al* (2021).

6. Conclusions

In October 2022, ICRP organised a workshop on the 'Review and Revision of the System of Radiological Protection: A Focus on Research Priorities'. The workshop, which was a side event of the European Radiation Protection Week in Estoril, Portugal, offered the international community an opportunity to comment on a recent publication issued by ICRP on 'Areas of research to support the system of radiological protection' (Laurier *et al* 2021). Specifically, the workshop focused on areas of research to support radiological protection, considering the evolution of the System of Radiological Protection developed by ICRP, and aiming to complement research priorities promoted by other international organisations.

At the workshop, the publication of Laurier *et al* (2021) was summarised. Then, views on priorities for research to support radiological protection were presented by a number of international organisations: IAEA, IOMP, IRPA, ISR and ESR, NEA, and WNA. These views were complemented by European and regional organisations: ALLIANCE, EAN, EANM, EFOMP, ENISS, EURADOS, EURAMED, EURAMET, FORO, MELODI, NERIS, PIANOFORTE, and SHARE. A final panel discussion allowed for audience interaction to encourage additional views and feedback.

While the System was generally considered robust and applicable, it was acknowledged that various scientific, technological, and societal developments, which have taken place since the last ICRP general recommendations of were published (ICRP 2007), may have implications for radiological protection. Consequently, the recent initiative of ICRP to review the current System was greatly appreciated. All participants and organisations followed ICRP's view that further research in various areas will offer additional support in improving the System, in the short, medium, and long term.

Many research topics mentioned by the participants were in line with those identified by Laurier *et al* (2021). For example, quite a few research needs were identified in the medical sector due the dynamic development of new technologies in that sector. It was generally agreed that continuous scientific efforts towards quantification of radiation risks at low doses and dose rates are still needed, which should not only include cancer but also non-cancer health endpoints such as diseases of the circulatory system and cataracts. Even an 'all-hazards' or 'holistic' approach was discussed that also included non-radiation related health risks that might also be present, and its implications for the System.

It was noted that research will also mutually support education and training activities and, consequently, education and training was mentioned as a cross-cutting issue. Further research should include SSH, to inform for example on how to consider scientific uncertainties, communication of radiation-related risks, and the ethical foundation of the System.

Research topics in addition to those identified by Laurier *et al* (2021) included, for example, systematic research on lessons learned from the global COVID-19 pandemic and how these could inform the current review of the System. It was requested that current protection strategies may need to be adapted to military scenarios like those observed recently during the military conflict in the Ukraine or the detonation of a nuclear weapon, and how to apply the current radiological protection principles in such situations. A number of additional new technologies that are currently developed or on the horizon were identified that require continuous monitoring for their implications for radiological protection. Further research was considered important to support quantification of radiation-related doses and effects on various levels of organisation (including on the tissue and population level) and various examples were given, all meant to improve protection of humans and the environment.

It was also noted that radiological protection research would benefit from early involvement of multiple disciplines, not least from SSH.

On a broader perspective, the question was raised how radiation research and radiological protection can contribute towards the 17 SDGs announced by the UN in 2015, to support a sustainable development of the world by 2030 (UN General Assembly 2015).

In conclusion, there was general consensus that continuous further research efforts are needed to make sure that the System remains fit for purpose and reflects any scientific, technological, and societal developments. Any change to the System should, however, be preceded by a thorough impact assessment before a final decision on its implementation is made.

Data availability statement

No new data were created or analysed in this study.

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