MEMORANDUM • **OPEN ACCESS**

Summary of the 2021 ICRP workshop on the future of radiological protection

IOP Publishing J. Radiol. Prot. 42 (2022) 023002 https://doi.org/10.1088/1361-6498/ac670e

Journal of Radiological Protection

RECEIVED
21 March 2022

REVISED
5 April 2022

ACCEPTED FOR PUBLICATION
13 April 2022

PUBLISHED
27 May 2022

MEMORANDUM

Summary of the 2021 ICRP workshop on the future of radiological protection

W Rühm[1], C Clement[2,*], D Cool[2], D Laurier[3], F Bochud[4], K Applegate[5], T Schneider[6], S Bouffler[7], K Cho[8], G Hirth[9], M Kai[10], S Liu[11], S Romanov[12] and A Wojcik[13,14]

[1] Helmholtz Centre Munich, German Research Centre for Environmental Health, Ingolstaedter Landstraße 1, D-85764 Neuherberg, Germany
[2] International Commission on Radiological Protection, 280 Slater Street, Ottawa, Ontario K1P 5S9, Canada
[3] Institut de radioprotection et de Sûreté Nucléaire, BP 17–92262 Fontenay-aux-Roses Cedex, 31 avenue de la Division Leclerc, 92260 Fontenay-aux-Roses, Île-de-France, France
[4] Lausanne University Hospital and University of Lausanne, Rue du Bugnon 21, CH-1011 Lausanne, Switzerland
[5] University of Kentucky College Medicine, 800 Rose Street MN 150, Lexington, KY 40506, United States of America
[6] Nuclear Protection Evaluation Centre, 28, rue de la Redoute, F-92260 Fontenay aux Roses, France
[7] Radiation Protection Science Division, UK Health Security Agency, Didcot, Oxon OX11 0RQ, United Kingdom
[8] Korea Institute of Nuclear Safety, PO Box 114, Yuseong, Daejeon 305-338, Republic of Korea
[9] Australian Radiation Protection and Nuclear Safety Agency, PO Box 655, Miranda, NSW 1490, Australia
[10] Nippon Bunri University, 1727 Ichigi, Ōita 870-0397, Japan
[11] China Institute of Atomic Energy, PO Box 275 (1), Beijing CN-102413, People's Republic of China
[12] Southern Urals Biophysics Institute, Ozyorsk, Chelyabinsk Region, Russia
[13] Centre for Radiation Protection Research, Stockholm University, Svante Arrheniusväg 20C, 106 91 Stockholm, Sweden
[14] Institute of Biology, Jan Kochanoski University, 25-406 Kielce, Poland
[*] Author to whom any correspondence should be addressed.

E-mail: sci.sec@icrp.org

Keywords: radiological protection, workshop, ICRP

Abstract

The International Commission on Radiological Protection (ICRP) has embarked on a process to review and revise the current System of Radiological Protection ('the System'). To stimulate discussion, the ICRP published two open-access articles: one on aspects of the System that might require review, and another on research that might improve the scientific foundation of the System. Building on these articles, the ICRP organized a Workshop on the Future of Radiological Protection as an opportunity to engage in the review and revision of the System. This digital workshop took place from 14 October–3 November 2021 and included 20 live-streamed and 43 on-demand presentations. Approximately 1500 individuals from 100 countries participated. Based on the subjects covered by the presentations, this summary is organized into four broad areas: the scientific basis, concepts and application of the System; and the role of the ICRP. Some of the key topics that emerged included the following: classification of radiation-induced effects; adverse outcome pathway methodologies; better understanding of the dose–response relationship; holistic and reasonable approaches to optimization of protection; radiological protection of the environment; ethical basis of the System; clarity, consistency and communication of the System; application of the System in medicine and application of the principles of justification and optimization of protection.

1. Introduction

Since its foundation in 1928, the International Commission on Radiological Protection (ICRP) has developed recommendations and guidance with the aim of contributing to the health and well-being of people, and subsequently the environment, through the safe use and management of ionizing radiation. The ICRP is an independent, non-governmental organization, which currently includes the Main Commission, Scientific Secretariat, four active committees (Committee 1 on 'Radiation Effects', Committee 2 on 'Doses from Radiation Exposure', Committee 3 on 'Radiological Protection in Medicine', and Committee 4 on

'Application of the Commission's Recommendations'), and a series of task groups. The results of the ICRP's efforts have been presented at a variety of radiation protection venues and in various publications. Since 1959, the ICRP has published approximately 150 reports on various topics, the most recent being ICRP *Publication 150* on 'Cancer Risk from Exposure to Plutonium and Uranium' (ICRP 2021a). While most of these publications deal with aspects relevant for certain applications of ionizing radiation, a few are of a more fundamental nature, describing general aspects of the entire System of Radiological Protection ('the System'). The most recent of these general recommendations is ICRP *Publication 103*, 'The 2007 Recommendations of the International Commission on Radiological Protection' (ICRP 2007).

Almost 15 years have passed since the publication of the 2007 Recommendations (ICRP 2007), which have seen considerable advances in radiation science and technology, as well as events and developments that have affected global societal values, risk perception and risk communication. The latter include the accident at Fukushima Daiichi Nuclear Power Plant (FDNPP) in 2011, climate change due to human activities in the energy sector, and, more recently, the coronavirus disease 2019 pandemic. To account for, consider and reflect on these and many other developments, the ICRP has embarked on a new cycle to review the System with the goal of issuing a successor to ICRP *Publication 103* (ICRP 2007) in about a decade.

To stimulate and encourage discussions on this, the ICRP recently published two open-access articles. The first article, entitled 'Keeping the ICRP Recommendations Fit for Purpose', includes reflections of the ICRP Main Commission of the previous term (which ended on 30 June 2021) on aspects of the System that might require review (Clement *et al* 2021). The second article, entitled 'Areas of Research to Support the System of Radiological Protection', discusses future short-, mid- and long-term research, which may have the potential to inform the scientific foundation of the System (Laurier *et al* 2021). Some of the identified research gaps are currently under review by ICRP task groups or by other organizations in the fields of radiation protection and broader radiation sciences.

It is important to note that while the ICRP is the steward of the System, the System exists for those who use it to protect patients, workers, the public and the environment. Consequently, collaboration with all of those using and benefiting from the System is essential. Consequently, over the next decade, the ICRP will work in a collaborative spirit to develop the next set of general recommendations that will shape radiation-related policy, practice, guidelines and regulations around the world. The two articles mentioned above represent key steps in that process. Based on many conversations in recent years and ICRP experience, these papers summarize—without the claim of being exhaustive—the topics considered important by the ICRP Main Commission for the future of radiological protection.

Along these lines, in October 2021, the ICRP organized a digital workshop—'Workshop on the Future of Radiological Protection' ('the Workshop')—as an opportunity to engage with its stakeholder community in the review and revision of the System, based on the two open-access articles mentioned above. The Workshop was organized to offer a platform where all those interested in this process could respond to these articles, express their thoughts and provide feedback. This article summarizes the presentations at the Workshop, and highlights contributions to the discussions considered relevant by the Main Commission.

The Workshop marks the beginning of discussions encouraged by the ICRP on the review of the System. Similar events will be held in the future to continue to support this discussion, such as workshops on the work-in-progress of individual task groups, and webinars to accompany the publication of new reports. The biennial ICRP symposia on the System will be milestone events in this process.

2. Organization and participation

2.1. Programme outline

The Workshop took place online from 14 October–3 November 2021. The programme was developed based on an open call for contributions responding to the 'Fit for Purpose' paper (Clement *et al* 2021) or any other subject related to the review and revision of the System.

This resulted in a comprehensive programme including 20 live-streamed and 43 on-demand presentations. The latter were a mix of short videos and extended abstracts. The live-streamed presentations were organized into four sessions over 19 and 20 October 2021: 'The Big Picture', 'Risks & Effects', 'Radiological Protection Concepts' and 'Application & Practice'.

The online platform enabled interaction between presenters and participants through chats attached to each live-streamed session and on-demand presentation. In addition, each live-streamed session included ample time for live questions and answers. Recordings of the live-streamed sessions were available during the Workshop so that interaction could continue through the chats.

The material from the Workshop, including the chats mentioned above, will be available to view online for the foreseeable future on the ICRP website at https://icrp.org/page.asp?id=510.

2.2. Participation

Registration was required for all participants, with a flexible four-tier registration fee including a zero-cost option to ensure that there was no financial barrier to participation while still allowing the possibility to cover some of the costs of the Workshop. Regardless of which tier was chosen, access to the Workshop was identical. Those who registered at the highest level were recognized on the platform and on the ICRP website.

In total, 1456 people from 97 countries and six continents registered for the Workshop. The four live-streamed sessions were well attended, with 826 attendees for 'The Big Picture', 643 attendees for 'Risks & Effects', 608 attendees for 'Radiological Protection Concepts' and 521 attendees for 'Application & Practice'. During the Workshop, the 43 on-demand presentations were visited 7294 times. This high level of participation reflects worldwide interest in the review and revision of the System, and the ICRP's priority to ensure that participation is accessible, open, transparent and meaningful.

3. Key points

Based on the subjects covered by the presentations submitted, this summary of the Workshop is organized into four broad areas: the scientific basis, concepts and application of the System; and the role of the ICRP. The details supporting this summary of key points are found in the sections that follow, which review each presentation relevant to the review and revision of the System.

3.1. Scientific basis of the System

One of the key topics that emerged related to radiation effects was the distinction made in the System between stochastic effects and tissue reactions for protection purposes, challenged, for example, by Trott (2021). The question of the classification of radiation-induced effects was one of the topics raised in the 'Fit for Purpose' paper (Clement *et al* 2021). The Workshop reinforced the need to review the way this is handled in the System to see whether improvement or clarification might be necessary and possible. In addition, the difficulty of interpreting radiation detriment as an integrated indicator of stochastic effects was discussed, in relation to the contribution that can be made by introducing the concept of disability-adjusted life-years (DALYs) (Grambow 2021, Vaillant *et al* 2021).

Another topic was the emerging use of adverse outcome pathway (AOP) methodologies. These were regarded as essential tools, for example, to explore the interplay between various stressors, such as chemicals and ionizing radiation. This aspect has not been addressed thus far in the System (Burtt *et al* 2021).

In addition, several presentations focused on better understanding of the dose–response relationship, for example, by considering potential thresholds (Jeffries 2021), the linear no-threshold (LNT) model (Hamaoka 2021), the role of stem cell competition (Sasaki *et al* 2021) and the models used to describe radiation-related chronic risks (Bando *et al* 2021). Informed by these discussions and two pre-existing ICRP working parties, shortly after the Workshop, ICRP prioritized the establishment of task groups on several topics, including cancer risk models and non-radiation factors in the calculation of detriment (ICRP 2021b).

Further research was proposed to explore possible effects of parental radiation doses before conception on adverse outcomes in the offspring (Mathews 2021). After the Workshop, the ICRP established Task Group 121 on 'Effects of Ionising Radiation Exposure in Offspring and Next Generations' to review and assess the scientific literature in this area. This task group had previously been informed by a preparatory working party under ICRP Committee 1 (ICRP 2021b).

Additional topics addressed included radiation risks for non-human biota (Cromnier *et al* 2021), consideration of research gaps in the use of radioprotective substances (Filimonova *et al* 2021) and the role of risk uncertainties in communication strategies (Garnier-Laplace *et al* 2021, Malone 2021, Sasaki *et al* 2021).

Protection of non-human biota was addressed with respect to radiation risk (Cromnier *et al* 2021), and work undertaken to develop dosimetry further (BenDriss *et al* 2021, Gomina *et al* 2021).

Several of these topics were addressed by Laurier *et al* (2021).

3.2. Concepts of the System

As expected, optimization of protection received considerable attention. Several participants encouraged a more holistic approach to optimization, considering factors beyond the radiological to a greater extent than often seen today (Andresz *et al* 2021, Lamarre *et al* 2021, Magnússon *et al* 2021) and better involvement of stakeholders to address public perception and concerns (Lecomte 2021). To support this, the ICRP could create a rigorous quantitative scientific framework for the trade-off between benefit and harm (Malone 2021). The United Nations (UN) Sustainable Development Goals could provide a framework to balance societal, environmental and economic risks and impacts (Mayall *et al* 2021).

Furthermore, several participants cautioned against over-conservatism in radiological protection, addressing the need for a more reasonable approach to optimization of protection, using realistic-dose estimates, reinforcing that optimization is not minimization, and potentially using the context of natural background exposure to inform decisions (Coates 2021). Concerns were expressed that elements of the System and its implementation have become overly conservative (Lorenz 2021, Magnússon *et al* 2021, Sasaki *et al* 2021). The work of ICRP Task Group 114 on reasonableness and tolerability is addressing an important part of this topic (Schneider *et al* 2021).

Some participants supported further development of radiological protection of the environment, for example, considering protection of ecosystem services (Cromnier *et al* 2021), expanding the database of reference organisms to include unicellular organisms, which might be used to assess ecosystem health (Villegas Garcia 2021), and better addressing environmental impacts in justification and optimization of protection through the UN Sustainable Development Goals (Mayall *et al* 2021).

Several presentations addressed the importance of considering the ethical basis of the System. For example, the need to distinguish between ethical values related to the integrity of nature and values related to the health of humans (Martinez *et al* 2021), ethical issues associated with the protection of animals in the field of veterinary activities (Cromnier *et al* 2021, Pentreath 2021) and the intersection of ethical values relevant for both medical ethics and radiation protection (Malone 2021). This reinforces the proposal in the 'Fit for Purpose' paper to explicitly incorporate the ethical basis of the System alongside the scientific basis (Clement *et al* 2021).

Other conceptual issues that should be considered in the process include, for example, new demands for social licence; the principle of dose limits; review of the exposure situations; reconsideration of the definition of occupational exposure; a review of the quantities used for dose; examination of the scope of application; explicit consideration of application to natural radiation; use of a linear model for relating dose and effects; use of the word 'contamination' and consideration of the epistemological constraints of the scientific basis of protection (González 2021).

3.3. Application of the System

During the Workshop, it was acknowledged several times that the System is robust, fit for purpose and has performed well (Johnston 2021, Sasaki *et al* 2021), but that its implementation is often challenging.

Several presenters noted that increasing clarity and consistency, as well as simplicity, especially to aid communication, are important (Johnston 2021, Petrová 2021). Similarly, the importance of communication to inform radiation-related risks and associated uncertainties, and more generally to inform about the complexity of the System, was stressed several times (Andresz *et al* 2021, Garnier-Laplace *et al* 2021, Johnston 2021, Magnússon *et al* 2021, Martinez *et al* 2021, Moores and Mattsson 2021, Petrová 2021, Vassileva and Holmberg 2021, Wilkins 2021). ICRP documents and recommendations can be difficult to read, which may lead to misinterpretation of dose limits, dose constraints and reference levels; uncertainties in dose measurements and health effects; application of optimization; and the LNT model (Chambers 2021, Lorenz 2021).

Application of the System in medicine was addressed specifically in several presentations. These stressed, for example, the need for improvements in education and training of medical staff (Nadareishvili *et al* 2021), the importance of establishing national diagnostic reference levels (DRLs) for computed tomography (CT) scans (Bernardo *et al* 2021), specific aspects of risk perception in the medical field and the use of effective dose (Moores and Mattsson 2021), continued rapid advances in medical technologies (García-Fernández *et al* 2021) and the recurrent use of CT imaging (Vassileva and Holmberg 2021). A strict quality-dose management programme is also important for radiological protection in medicine (Cruz and Jornada 2021).

Justification and optimization of protection were raised not only as concepts (discussed above) but also with respect to challenges in implementation. For example, justification and optimization and the use of reference levels were identified as areas that would benefit from additional guidance (Cromnier *et al* 2021), as well as application of the System for radon (Petrová 2021). With respect to optimization below reference levels, difficulties encountered in the development of radon action plans, and implementation of justification in emergency exposure situations require clarification (Janžekovič 2021).

The link between nuclear safety and radiation protection should be clarified, and further guidance is expected on how to apply risk constraints for workers in the optimization process (Cromnier *et al* 2021).

The potential use of online dosimetry for occupational exposures using motion-tracking software in simulated radiation fields was discussed for application in fluoroscopically guided interventional procedures (Vanhavere 2021).

More than once, participants emphasized that recommendations must be implementable and proposed changes must be justified (Magnússon *et al* 2021).

3.4. The role of the ICRP

Several presentations addressed the role of the ICRP. These included valuable advice for the continuing process of the review and revision of the System, and the need for international efforts to enhance education and training in radiation research and radiological protection (Caruana and Pace 2021, Higley *et al* 2021, Joseph *et al* 2021).

Interactions between the ICRP, other international organizations, and the radiological protection community in general were considered particularly important (Johnston 2021, Magnússon *et al* 2021). Openness, accessibility and transparency are crucial to the success of the review and revision of the System.

In addition, it was proposed that the ICRP review its governance framework to assess and ensure its independence (Malone 2021).

3.5. Actions shortly after the Workshop

A regular, biannual meeting of the ICRP Main Commission was held a few weeks after the Workshop, at which the Main Commission established Task Group 121 on 'Effects of Ionising Radiation Exposure in Offspring and Next Generations' (which had been informed previously by a preparatory working party under ICRP Committee 1) and prioritized the establishment of task groups on several topics, including the following: radiological protection in biomedical research; cancer risk models; ecosystem services approach for protection of the environment; effective dose in medicine; justification, and non-radiation factors in detriment (ICRP 2021b).

To continue to ensure accessible, open, transparent and meaningful collaboration during the review and revision of the System, the ICRP confirmed its intention to hold regular workshops on work in progress (virtual, in-person and hybrid), and webinars on completed publications, and announced open solicitations of expressions of interest for experts to join future task groups when they are established (ICRP 2021b).

4. Live-streamed presentations

4.1. Session 1: The Big Picture

This 3 h live-streamed session took place on 19 October 2021, moderated by ICRP Scientific Secretary and CEO **Christopher Clement**. It consisted of five oral presentations and 30 min of questions and answers.

ICRP Chair **Werner Rühm** began the session presenting 'Review & Revision of the System of Radiological Protection', describing some of the issues already being addressed, emphasizing the purpose of the Workshop, and outlining the planned decade-long process for which international collaboration will be essential. He emphasized the need to improve the clarity and consistency of ICRP's recommendations and to simplify aspects of the System where appropriate (Rühm 2021).

Miroslav Pinak, on behalf of **Peter Johnston** of the International Atomic Energy Agency (IAEA), presented 'Working Together on Development of International Guidance Documents in Radiation Safety', outlining the role of the IAEA in radiological protection and examples of cooperation with the ICRP, bilaterally and through the Inter-Agency Committee on Radiation Safety. He noted that the System is robust, fit for purpose and has performed well and that IAEA member states need time to fully implement what has already been developed and that many of the member states' challenges are related to implementation rather than the System itself. Nonetheless, he supported increased clarity and consistency, as well as simplicity, especially to aid communication (Johnston 2021).

Sigurður Magnússon, International Radiation Protection Association (IRPA), presented 'IRPA Perspective on the Review of the System of Radiological Protection', focusing on three recent consultations: a summary of the outcome of an IRPA consultation on 'Is the System of Protection Fit for Purpose and Can it be Readily Communicated?' (Coates and Czarwinski 2018); an IRPA consultation on 'Reasonableness in Optimisation of Protection' (IRPA 2021); and initial feedback gathered by a recently established IRPA Task Group on 'Review of the System of Radiological Protection'. The latter has 30 members from 20 IRPA Associate Societies representing thousands of professionals from all regions of the world. There is strong agreement from those responding on several points. These include:

- communication about the System is challenging due to its complexity;
- communicating with the public on radiation and risk is important;
- there is concern that the System has become overly conservative and applications in the regulatory system are even more conservative;
- recommendations must be implementable;
- there is value in stability, and changes must be justified;

- the ethical basis of the System should be incorporated explicitly into ICRP recommendations, including a focus on ethics in communicating about the System and
- optimization should be holistic, including non-radiation effects, stressing that it is not minimization, promoting reasonable caution to avoid undue conservatism, and should be supported by practical recommendations.

However, there was disagreement on whether to continue to use the LNT model as a basis for protection (Magnússon *et al* 2021).

Kathryn Higley, University of Oregon, USA, presented 'What Should be the Role of Higher Education in the Future of Radiological Protection?', focusing on the importance of formal education, training and work experience in radiological protection, more specifically on how academic programmes can be enhanced through international engagement. The subsequent discussion explored possibilities for engagement with or through the ICRP, IRPA and other means (Higley *et al* 2021).

Flavious Bobuin Nkubli, University of Maiduguri, Nigeria, presented 'Keeping the ICRP Recommendations Fit for Purpose and the Need for a Global North–South Collaboration', focusing on the need for world-wide collaboration to ensure that recommendations are fit for purpose for all end-users in all parts of the world. Challenges include language gaps, cultural differences, varying levels of infrastructure, and areas impacted by conflict and crisis (Nkubli *et al* 2021).

4.1.1. Discussion

During the discussion that followed, in response to a question about how citizens can be involved in the review and revision of the System, Werner Rühm noted the importance of involvement of the ultimate stakeholders—the patients, workers and the public who the System is designed to protect. Miroslav Pinak recalled the mechanisms that the IAEA uses to gather input from Member States. Sigurður Magnússon referred to the IRPA document 'Practical Guidance for Engagement with the Public on Radiation and Risk' available on the IRPA website. Christopher Clement mentioned ICRPæDIA, an effort by the ICRP to make its work more accessible to a broader audience.

Flavious Nkubli and Werner Rühm spoke about means of international cooperation and collaboration, including the ICRP mentorship programme and the now-familiar use of online meetings.

The need for openness and transparency in the review and revision of the System was shared by the speakers in this session.

4.2. Session 2: Risks & Effects

This 2 h live-streamed session took place on 19 October 2021, moderated by ICRP Committee 1 Chair **Dominique Laurier**. It consisted of five oral presentations and 30 min of questions and answers.

John Mathews, University of Melbourne, Australia, presented 'Revisiting Next Generation Effects of Ionising Radiation'. Most epidemiological results have not shown an excess risk of adverse effects in the offspring and next generations of persons exposed to radiation. He criticized a recent study of de-novo gene mutations in children of parents exposed to Chernobyl radiation before conception using whole-genome sequencing because the detected de-novo gene mutations were predominantly single nucleotide variants but did not consider gene deletions and other copy number variants. To allow a direct test of the hypothesis that parental radiation doses, before conception, predict adverse outcomes in their offspring, he proposed that a large national epidemiological study be conducted in Australia to link parental records of medical radiation to the health outcomes of their children (Mathews 2021).

Nobuhiko Ban, Nuclear Regulation Authority, Japan, presented 'Possible Improvements of Methodology for Calculating Radiation Detriment in the Future'. Being part of the work of ICRP Task Group 102, this presentation is discussed in the section dedicated to ICRP task groups (Ban *et al* 2021).

Jacqueline Garnier-Laplace, Division of Radiological Protection and Human Aspects of Nuclear Safety, OECD Nuclear Energy Agency (NEA), presented 'Reducing Uncertainties in Low Dose/Low Dose Rate Health Risks Requires International Networking in Research Implementation and its Communication to Stakeholders'. She detailed the activities conducted within the framework of the High-Level Group on Low-Dose Research (HLG-LDR) operating under the auspices of the NEA's Committee on Radiological Protection and Public Health. The HLG-LDR aims to facilitate global networking of low-dose research-funding organizations and research-implementing organizations. This initiative also integrates a policy-oriented communication strategy on risk uncertainties (Garnier-Laplace *et al* 2021).

Yuichi Tsunoyama, Kyoto University, Japan, presented 'A Proposal for the Application of Mathematical Models that Accurately Approximate Measured Data to Radiation Protection'. He described a mathematical model, the Whack-A-Mole (WAM) model, which aims to reproduce the dose-rate effects observed in genetic research experiments in plants and animals, such as mice. He is now investigating the applicability of the

WAM model to chromosome aberrations. Using the WAM model as an example, he suggested further consideration of the incorporation of new mathematical models in the field of radiological protection (Tsunoyama *et al* 2021).

Klaus Trott, Department of Radiation Oncology, Technical University of Munich, Germany, presented 'What is Needed to Keep ICRP Recommendations Fit for Future'. In his presentation, he challenged the distinction between stochastic effects and tissue responses. Using various examples, including diseases of the circulatory system, cataracts, cognitive effects and heritable effects, he argued that the classification that is currently applied in the System is not compatible with current radiobiological evidence. He concluded that a new System should not be based on a classification of radiation effects in specific organs or tissues but on specific exposure situations (Trott 2021).

4.2.1. Discussion

Many issues of pertinence for the System were raised in the discussion. Most of them considered issues related to the characterization of effects, including the quantification of radiation risks among offspring of exposed individuals and their integration into the System, the validity of the current classification of radiation effects between stochastic and tissue reactions, the shape of the dose–risk relationship for cancers and the validity of the LNT model, and the consideration of a dose-rate effect and the validity of the dose and dose-rate-effectiveness factor (DDREF).

Others considered potential improvements in the System, including the clarification of the process of detriment calculation and of its use as a risk indicator or as a management tool, the consideration of uncertainties at low doses in radiation detriment, and the diversity of modelling approaches for the quantification of radiation effects.

Finally, some points were more operational, such as the feasibility and pertinence of developing open-source software for the calculation of radiation detriment, interest in further development of the interactions between the ICRP and special liaison organizations, and the need for improvement in communication and training.

4.3. Session 3: Radiological Protection Concepts

This 2 h live-streamed session took place on 20 October 2021, moderated by ICRP Vice Chair **Donald Cool**. It consisted of five oral presentations and 30 min of questions and answers.

Nicole Martinez, Clemson University, USA, and **Friedo Zölzer**, University of South Bohemia, Czech Republic, presented 'Consistency and Complementarity of Ethical Values Across the System and Practice of Radiological Protection'. They reviewed the current ICRP views on ethics and ethical values, starting with ICRP *Publication 138* (ICRP 2018), and the values related to environmental radiological protection from ICRP *Publication 91* (ICRP 2003a). They next described the work of ICRP Task Group 109 looking at the ethics of radiological protection of patients when using radiation in medicine, noting the similarities of the principles of biomedical ethics with ICRP values. A further extension to the area of veterinary practice noted the need to distinguish between values related to the integrity of nature and values related to the health of humans. While different ICRP publications use different sets of values, these sets are not inconsistent with each other, and demonstrate insight into the evolution of societal values. The complementarity between the proposed value sets needs to be considered and clarified as the ICRP moves forward (Martinez and Zölzer 2021).

Jean-François Lecomte, Institut Radioprotection Sûreté Nucléaire, France, presented 'Summary of the Third SFRP [Société Française de Radioprotection]/IRPA Workshop on the Application of the Concept of Tolerability'. He introduced the topic, noting that the optimization principle is the cornerstone of the System, and then discussed the set of workshops initiated by the SFRP. Workshops were held in 2017, 2018 and 2021, with the first two workshops focused on the search for reasonableness, and the third workshop focused on the question of tolerability. The SFRP workshops used case studies of radon at home, naturally occurring radioactive materials, and nuclear power plant dismantling to investigate the issue, including the question of the boundary between tolerable and unacceptable, and a rationale for the selection of criteria. He noted that the level of risk for this boundary is not necessarily the same in all situations and that it is important to consider all hazards involved. Also critical is the sustainability of the decisions, and the involvement of stakeholders in the discussions (Lecomte 2021).

Roger Coates, former IRPA President, UK, presented 'The Need to Review Low-dose Decision-making in Radiation Protection'. He noted that the context of a particular situation is important in considering how to implement the System, using an example comparing the clearance of materials from a practice with the dose that might be received while on holiday in an area where background radiation rates are greater than average. He suggested that a value of 'common sense' should be added in application of the System, and that the context of natural background exposure could be useful to inform decisions. There are challenges in

decision-making, including the link to tolerability of risk and public perception and concerns. He concluded by noting that a more relatable approach in decision-making could be made by using reference background radiation levels, reinforcing that optimization is not minimization; prioritization of public engagement; and the use of realistic estimates to avoid over-conservatism (Coates 2021).

Sylvain Andresz, Centre d'étude sur l'Evaluation de la Protection dans le domaine Nucléaire, France, presented 'Application of the Graded Approach for the Radiation Protection of Workers: Examples and Reflections from European ALARA [as low as reasonably achievable] Networks'. He began by examining what is meant by the phrase 'graded approach', and then used several examples from the European ALARA network to illustrate the wide variability in application. He then proposed a generic scheme for making decisions, including preliminary analysis and categorization of the situation with radiological and other criteria. He suggested that the highest regulatory effort should be allocated to the sectors/installations with the highest risk, with effort being commensurately less for the others. He noted that communication and stakeholder involvement were vital in the process. He concluded by noting that a graded approach in radiological protection may take advantage of the control mechanisms already existing/defined in other regulations and that the aim should be an integrated and eventually holistic approach (Andresz *et al* 2021).

Abel González, Argentine Nuclear Regulatory Authority, Argentina, presented 'Prospects on the ICRP Paradigm for Radiological Protection'. He began by noting that the current paradigm for protection is based on sound science and is comprehensive, but that there are opportunities for further refinement based on scientific information on the epistemology of radiation effects, and contemporary social demands on radiological protection. He made 12 suggestions for consideration: new demands for social licencing (i.e. the ongoing trust and acceptance by the public of an institution/company's standards of practice and operating procedures); the principle of dose limits; incorporation of ethics; review of the exposure situations; reconsideration of the definition of occupational exposure; refinement of the approach to medical exposure; a review of the quantities used for dose; examination of the scope of application; explicit consideration of application to natural radiation; clarification of 'LNT'; use of the word 'contamination' and consideration of the epistemological constraints of the scientific basis of protection (González 2021).

4.3.1. Discussion

The open discussion focused upon the themes of tolerability and reasonableness, application of optimization in various areas, and the importance of stakeholder and public involvement. These areas are critical to the effective implementation of the System, the perception of involved or affected individuals, and the sustainability of decisions. There are opportunities to refine and clarify concepts and principles to better facilitate both the comprehensibility of the System and its application.

4.4. Session 4: Application & Practice

The 2 h live-streamed session took place on 20 October 2021, moderated by ICRP Committee 4 Chair **Thierry Schneider**. It consisted of five oral presentations and 30 min of questions and answers.

Douglas Chambers, TKI Radiological Sciences Arcadis Canada Inc., Canada, presented 'Updating the ICRP's Recommendations—a Practitioner's Perspective', emphasizing the difficulties encountered in presenting the ICRP's publications and recommendations to lay audiences and regulatory panels. He mentioned some challenges due to misinterpretation of the application of the concepts of dose limits, dose constraints and reference levels. He also recalled that application of the ALARA principle does not mean zero dose but relies on a balancing of factors. For the use of the LNT dose–response, he pointed out the importance of recalling that this is an assumption clearly linked with the concept of effective dose. However, Chambers suggests that it may not be possible to measure dose per se at low doses; in this case, the risks are low and often lost in the noise from background radiation (Chambers 2021).

Nina Cromnier, Swedish Radiation Safety Authority, Sweden (SSM), presented 'The Need for Bridging the Gaps Between Theory and Practice—an Authority's Perspective in Some Identified Areas', and listed some issues identified by the SSM for further clarification and adjustment among the ICRP recommendations. She first emphasized the gap between practice and theory for medical exposure situations. Although numerous ICRP publications deal with the practical use of the radiological protection system in medical practices, she called for better integration of medical exposures into the System. For emergency exposure situations, she mentioned the need to improve the categorization of workers involved in emergency and recovery activities. In the design and operation of nuclear power reactors, she insisted on a link between nuclear safety and radiation protection to better address specific radiological criteria to cope with potential exposure of workers. Further guidance is expected from the ICRP on how to apply risk constraints to workers in the optimization process. To protect the environment, she mentioned the importance of expanding the System with further considerations on the protection of ecosystem services. Finally, she called for discussion on ethical issues associated with the protection of animals in the field of veterinary activities (Cromnier *et al* 2021).

Helena Janžekovič, Slovenian Nuclear Safety Administration, Slovenia, presented 'ICRP 103 and Authorisation and Inspection Processes', explaining the lack of understanding of some of the concepts introduced by the ICRP for some users of sources, regulatory staff, and qualified experts, among others. She mentioned the need for further guidance for practical implementation, notably for justification, use of dose constraints and optimization with reference levels. For the latter, she reported the difficulties encountered in the development of a national radon action plan or even the decision to be made for evacuation in case of a nuclear accident, as observed after the FDNPP accident (Janžekovič 2021).

Dlama Zira Joseph, Federal University of Lafia, Nigeria, presented 'Education and Training in Radiation Protection: Bridging the Gap to Keep ICRP Recommendations Fit for Purpose', and highlighted the difficulties that developing countries face when setting up sustainable and adequate training programmes. He mentioned the importance of addressing education and training for radiation protection using an integrated and holistic approach. To foster the development of education and training programmes, he proposed the harmonization of content and the organization of assistance of trainees with the support of the ICRP (Joseph *et al* 2021).

Jim Malone, Trinity College Dublin, Ireland, presented 'ICRP and a Century of Governance and Ethics for Radiation Protection in Medicine', emphasizing the importance for the ICRP to review its governance framework to ensure and assess its independence. He mentioned that the recommendations have to be considered in the light of ethical values relevant for both medical ethics and radiological protection. He questioned the attempts of the ICRP to create a rigorous quantitative scientific framework for the trade-off between benefit and harm and called for increasing considerations in the future regarding uncertainty (Malone 2021).

4.4.1. Discussion

The discussion was focused on three main topics: application of the principle of justification; application of the principle of optimization; and education and training, and risk communication.

For application of the principle of justification, the need to review its application in different domains was emphasized, with a specific focus on the medical sector, and exploration of the role of authorities/regulators, experts and stakeholders as well as the relevant criteria to assess justification. Also mentioned was the importance of considering the application of justification at the initial stage of practice and during all life phases. Ethical criteria were considered useful for assessing the application of this principle.

For application of the principle of optimization, the discussion was balanced between the call for simplification and an improved understanding of the current System. Clarification of application of the concepts of dose limits, dose constraints, and reference levels was also emphasized. Further guidance on the practical application of optimization in the medical sector was requested as well as clarification concerning the rationale and use of ethical considerations for its application below reference levels in different exposure situations. In the same spirit, several participants called for introducing dose cut-off values, while others questioned the rationale and usefulness of these. Finally, it was proposed that lessons be drawn from management of the coronavirus disease 2019 pandemic (particularly development of the public's co-expertise and the need for experts to remain) and consideration of how lessons from management of the pandemic might change the current approach in radiological protection.

For education and training, and risk communication, discussion participants stressed the need for the ICRP to establish a strategic plan and a roadmap to foster the education and training of radiological protection professionals on the System. To this end, it was proposed that cooperation with national and international organizations be engaged to implement a roadmap on education and training. Furthermore, to improve the communication and dissemination of the ICRP recommendations, the preparation of summaries for the public was emphasized, as well as the organization of a dialogue with different stakeholders to encourage and measure feedback on implementation of the recommendations.

5. On-demand presentations

The on-demand presentations focused on various applications of ionizing radiation and related radiological protection issues. They consisted of oral and written presentations, with participant comments and some responses by the authors and/or the ICRP membership. Short summaries of these presentations are given below, ordered as relevant for the individual ICRP Committees.

5.1. Summary of Committee 1 related presentations

Julie Burtt, Canadian Nuclear Safety Commission, Canada, *et al* presented 'Advancing the Adverse Outcome Pathway (AOP) in Radiation Research: An International Horizon-style Exercise'. An international horizon-style exercise has been undertaken under the auspices of NEA's HLG-LDR to identify the most

important open questions regarding the use of the AOP framework in the field of radiation. AOPs are regarded as an essential tool to characterize the knowledge domain, define evidence gaps, and inform research directions based on knowledge from both the chemical and radiation research communities. In the first phase of the exercise, research questions on the use of AOP in radiation research were collected. Questions included using AOP to better understand the effects of radiation exposure, provide insight into individual sensitivity to radiation, make a link between radiation exposure and the immune system, decipher the role of epigenetic changes in adverse outcomes, shed light on DNA repair mechanisms, and support radiation risk assessment. Currently, the questions are being ranked to identify the top candidates in order to survey the broad research community with the aim of directing future collaborative research projects (Burtt *et al* 2021).

Marina Filimonova, Siberian Medical Radiological Research Centre, Russian Federation, *et al* presented 'A Promising Concept for the Development of Means for the Prevention of Radiation Pathologies'. The results suggest that selected nitric oxide synthase (NOS) inhibitors could be promising radioprotectors. Currently, only two radioprotectors are approved for use in radiotherapy to prevent normal tissue toxicities: amifostine and palifermin. However, both drugs induce side effects, so there is a need to develop radioprotectors with fewer side effects. Compounds capable of selective inhibition of endothelial and inducible NOS are promising candidates. It was demonstrated that NOS inhibitors, particularly N,S-substituted isothioureas, protect normal tissue from radiation toxicity in relatively safe doses. NOS inhibitors act by suppressing the endothelium-dependent eNOS/sGC/cGMP pathway of vascular relaxation and represent a promising class of future radioprotectors (Filimonova *et al* 2021).

Cameron Jeffries, South Australia Medical Imaging, Australia, presented 'Does the System of Radiological Protection Require Science to the Nth Degree to be Fit for Purpose?' It was suggested that the System could be simplified for the benefit of stakeholders by introducing a threshold dose below which no regulations are required. As an example of an area that would benefit from such modification, the adoption (or the local interpretation) of LNT has made it mandatory for medical staff to wear 7 kg lead aprons during long surgical procedures, even when these only include short x-ray examinations in the middle. This practice adds a risk of musculoskeletal injuries that is higher than the assumed risk of stochastic effects from the radiation dose absorbed without wearing an apron. Also, cost–benefit calculations show that the application of lead aprons is not justified. According to Jeffries, regulations are moving beyond an appropriate level of protection to prevent risk of harm regardless of economic or social factors. A new threshold model should be applied, with a threshold at 1 mSv, to make the System fit for purpose (Jeffries 2021).

Michiya Sasaki, Central Research Institute of Electric Power Industry, Japan, *et al* presented 'Issues Concerning the Carcinogenesis Risk and Implementation of the System of Radiological Protection'. It was stated that the System has changed over time, and while it is sufficiently robust, there is a need to add new knowledge and further improvements. In the low-dose range, cancer is the main detriment. Research in Sasaki's laboratory has focused on understanding the competition between normal and radiation-modified stem cells for residence in the stem cell niche, a process that will influence the shape of the dose response for radiation-induced cancer. Furthermore, it is important to clarify how to deal with uncertainty of risk in the low-dose range. Radiological protection must maintain a safety margin and avoid excessive conservatism. Finally, to keep the System fit for purpose, more attention must be given to optimization of nuclear waste management (Sasaki *et al* 2021).

Yutaka Hamaoka, Keio University, Japan, presented 'LNT Model is not an 'Assumption': Re-analysis of Epidemiological Data Empirically Supports LNT'. The Life Span Study data of atomic bomb survivors on cancer incidence was re-analyzed with the aim of finding the best evidence-based model for fitting data in the low-dose region. The rationale behind this study was to validate the opinion expressed by the ICRP that scientific evidence does not allow a conclusion to be drawn regarding whether the LNT model is appropriate for risk assessment of stochastic effects below 100 mSv. It was emphasized that the analysis should avoid three common and problematic approaches: aggregation/tabulation of individual-level data; restricting samples to the low-dose range; and incomplete model selection. The results demonstrate that the LNT model best fits the data, thus demonstrating the scientific basis of selecting it for use in radiological protection (Hamaoka 2021).

Ludovic Vaillant, Nuclear Protection Evaluation Centre, France, *et al* presented 'Radiation Detriment Calculation Methodology: Review of Current Non-radiation-related Parameters and Perspectives'. Calculation methodology of radiation detriment and perspectives of evolution have been reviewed recently by ICRP Task Group 102. In the calculation process, radiation detriment is estimated from nominal risk coefficients after adjustment for cancer severity. This adjustment relies on three parameters not related to radiation: the lethality fraction; a quality-of-life factor; and the relative years of cancer-free life lost. The ICRP recognizes that the radiation detriment calculation methodology needs to be revised, and an update is needed for these non-radiation-related parameters to reflect the evolution of scientific knowledge and expert

judgement on cancer severity. Possible ways to update this were described, and the pertinence and feasibility of the use of DALYs as a measure of radiation-induced harm were discussed. Work should be undertaken by the ICRP in this field in the coming years (Vaillant *et al* 2021).

Masanori Tomita, Central Research Institute of Electric Power Industry, Japan, *et al* presented 'Radiation-induced Stem Cell Competition and Dose-rate Effect'. Research in Tomita's laboratory has focused on the use of intestinal organoids to evaluate radiation-induced stem cell competition under conditions of high and low-dose-rate exposure. It was observed that irradiated stem cells exhibited a growth disadvantage when grown together with non-exposed cells in mixed organoids. However, when grown alone, irradiated stem cells survived better. These results suggest that radiation-induced stem cell competition can occur in the intestine, and the stem cell competition can explain the sparing effect of low-dose-rate irradiation compared with high-dose-rate irradiation. The findings are supported by a mathematical model. Consideration of the stem cell competition mechanism in cancer risk after low- and high-dose-rate exposure is important to keep the future System fit for purpose (Tomita *et al* 2021).

Bernd Grambow, SubaTECH, France, presented 'Radiological Risk in the Global Burden of Disease'. The contribution of radioactivity to the overall burden of disease has rarely been put in the context of overall pollution of the environment, despite the fact that it has high public interest. This point was illustrated using DALYs, a concept developed by the World Health Organization (WHO), to assess the global burden of diseases and to compare the impact of chemotoxic risk with those of many other risk factors. Results considering diverse situations of exposure to ionizing radiation were presented, such as the evacuated zones in Fukushima or the vicinity of future radioactive waste disposal sites. It was concluded that the ICRP should make an effort to help people to understand radiological risks in the overall context of other risks (Grambow 2021).

Masako Bando, Kyoto University, Japan, *et al* presented 'Unified Understanding of Biological Effects Caused by Radiation: Overcoming Linear Quadratic Model Difficulties'. The WAM model was presented as a unified description of biological effects caused by radiation. The basis for developing the WAM model was the inconsistency of data regarding the impact of dose rate on the frequency of radiation-induced DNA mutations. By considering cell exclusion effects, the WAM model can describe the effects of dose fractionation as a case of low-dose rate, without any need to apply the DDREF concept. In this way, the WAM model can be applied to predict the progress of tumour eradication during radiation therapy (Bando *et al* 2021).

5.2. Summary of Committee 2 related presentations

Mahmoud Gomina, Ibrahim Badamasi Babangida University Lapai, Nigeria, *et al* provided an extended abstract 'Assessment of Non-human Biota Dose at the El Amin University Proposed Site, Minna, Nigeria'. The dose rate for non-human biota in a location in Nigeria was estimated using the ERICA software. The main input data were the natural radioactivity levels coming from a previous study. The main conclusion was that these results could serve as baseline data for the assessment of possible anthropogenic enhancement of the total dose rate for non-human biota (Gomina *et al* 2021).

Seung-Chan Lee, Korea Hydro Nuclear Power Co., Korea, presented 'A Study for Dose Impact of MCR Operators in Nuclear Power Plants Under ICRP 30 and ICRP 60'. The dose delivered to the operators working in the main control room of a nuclear power plant was computed. The dose conversion factors proposed following ICRP *Publications 30* and *60* (ICRP 1991, 2007) were compared, and it was concluded that the dose contribution of tritium was negligible in both cases (Lee 2021).

Andrea Castillo, Universidad Nacional Autónoma de Nicaragua-Managua, Nicaragua, *et al* provided an extended abstract 'Calibration of a Dosimetric System in $H_p(3)$ Using a Cylindrical Phantom'. The study reported a calibration procedure for $H_p(3)$ dosimeters for the lens of the eye. This allowed a proposal for the use of this dosimetric service at the national level (Castillo *et al* 2021).

Hafssa BenDriss, Ibn Tofail University, Morocco, *et al* provided an extended abstract 'InterDosi-based Monte-Carlo Assessment of S-values on a Voxel-based Crab Phantom for Cs-137, Te-132 and Co-58'. The S-values associated with the incorporation of Cs-137, Te-132 and Co-58 in a crab phantom were computed according to the Medical Internal Radiation Dosimetry methodology. This calculation was performed for five main organs of a crab, with the InterDosi code used as an indicator of marine ionizing radiation pollution (BenDriss *et al* 2021).

Lynn Ninsiima, Atomic Energy Council, Uganda, *et al* provided an extended abstract 'Optimization of Dose for Adult Chest Computed Tomography Examinations: A Phantom Study'. The image acquisition parameters of a chest CT protocol (pitch and kilovoltage) were optimized to keep the signal-to-noise ratio above a certain level (Ninsiima *et al* 2021).

Filip Vanhavere, SCK-CEN, Belgium, presented 'Personal Online Dosimetry Using Computational Methods: the PODIUM Project and the Future of Active Dosimetry'. The European PODIUM project aims to

investigate the possibility of performing personal occupational dosimetry without a conventional measuring instrument (wearable monitoring badge). This presentation analyzed the case of fluoroscopic-guided interventional procedures. The PODIUM project proposes the use of 3D optical imaging to estimate the position and posture of workers in real time, together with dosimetric phantoms, as well as the exposure parameters of the fluoroscopy equipment. At present, it seems that certain exposure situations could benefit from this type of approach in the future but there are still important challenges to solve, such as monitoring the movements of the different workers in the room, and the position and role of the shielding accessories. Even if automated dosimetry without personal badges remains a long-term goal, the tools under development will undoubtedly be able to find applications more quickly in the field of education and training (Vanhavere 2021).

5.3. Summary of Committee 3 related presentations

David Nadareishvili, Beritashvili Centre of Experimental Biomedicine, Georgia, *et al* presented 'Attitudes of Staff Involved in Dental Radiological Procedures in Georgia Towards Radiation Protection and Safety: A Questionnaire-Based Study'. This study provides important information about the current knowledge and perception of dental staff about the use of radiological imaging and protection for dental patients. Over 100 responses, mainly from dentists, showed good training in the Basic Safety Standards, awareness of special needs for the protection of pregnant patients, and appropriate use of radiological imaging in patients. The survey also highlighted some gaps in knowledge that are opportunities for ongoing training, although it may not have been clear from the way that some questions were worded, only 55% of the respondents reported learning radiation safety from their training programme, and 25% of the respondents were not familiar with the term 'ALARA'. The survey was a well-coordinated effort by regulatory and professional bodies, so it may be repeated or enlarged over time (Nadareishvili *et al* 2021).

Michael Moores, International Radiotherapy Services Ltd, UK, *et al* presented 'Comments on the System of Radiological Protection' focusing on three areas of discussion in radiological protection: the wide variation in perception versus reality of risk; the assessment of dose and risk associated with the marked increase in use of CT examinations worldwide; and the use of effective dose in medicine. The interesting and provocative presentation showed data on gaps between how a knowledge expert in an area will perceive a specific risk compared with a non-expert, and how most individuals lack understanding of ionizing radiation risk compared with other activities. It was noted that risk cannot be eliminated but can be managed pragmatically through strengthening safety management and by understanding human behaviour and risk communication, which is very much a focus of the review/reflection for the next set of general recommendations by the ICRP (Clement *et al* 2021, Moores and Mattsson 2021).

Gonzalo García-Fernández, Universidad Politécnica de Madrid, Spain, *et al* discussed 'Impact of New Developments in the Commissioning of Operational Radiation Protection in Compact Proton Therapy Centres (CPTC)' and demonstrated how quickly the science and practice of proton therapy technologies has moved since ICRP *Publication 127* (ICRP 2014). An excellent overview of compact proton therapy centres and the evolution of dose delivery to patients was provided, focusing on the facility design for radiological protection that can also save costs. Monte-Carlo calculations, which differed from estimates from ICRP *Publication 127* (ICRP 2014) were provided. A 'ten commandments' list for the commissioning of new equipment provided ways to mitigate doses with concrete, ventilation, water and soil techniques (García-Fernández *et al* 2021).

Arícia Ravane Pereira da Cruz, Universidade Federal de Pernambuco, Brazil, *et al* presented 'Influence of Different Operating Modes (High, Normal and Low) and FOV (field of view) Sizes on Air Kerma Rate in Different Interventional Radiology Equipment' and described their experience in quality control testing of dose output for interventional procedures in room equipment and C-arm equipment. Outputs were measured when using low versus normal (medium) versus high modes of tube output, and with different FOVs. The results were expected in that there was a graded increase in dose with mode switch from low to normal to high; dose generally increased with smaller FOV, but less so with flat panel equipment. However, some results were unexpected in terms of dose and dose-rate variation between vendors and within the same equipment. This reinforced the essential need for a high-quality dose management programme (Cruz and Jornada 2021).

Jenia Vassileva, Radiation Protection of Patients Unit, IAEA, Austria, *et al* presented 'Radiation Protection Perspective to Recurrent Medical Radiological Imaging'. Evidence of increased cumulative effective doses (CEDs) in medical imaging of >100 mSv was described, along with a potential path forward. From 2017–2021, there were more than 20 publications showing CEDs of >100 mSv, predominantly from CT imaging, but also from interventional procedures and positron emission tomography/CT, mainly in developed nations, which occurred over a period from as little as 1 d but typically over 1–5 years. The

fraction of imaged populations worldwide receiving these doses, where evidence shows that health effects may occur, is consistently around 1%, and some publications provide general demographic information, which shows that not all cases are older and sick populations. The suggestions for addressing this new area included implementation of the IAEA Position Statement and Call for Action by nine international organizations, such as strengthening justification, use of standard-dose measurement in medical imaging records, strengthening education and training across stakeholders in this area and clarifying communication of benefit/risk regarding CEDs (Vassileva and Holmberg 2021).

Mônica Oliveira Bernardo, Hospital Miguel Soeiro-São Paulo, Brazil, *et al* presented 'Strategies to Implement Dose Reference Level in Tomography in Brazil: Preliminary Analysis', with data showing an excellent step towards the establishment of DRLs for CT examinations, and perhaps the first in Latin America. The pilot study used a combination of international methods to collect data quickly from 15 hospitals in eight states across regions in Brazil to provide an indication of the range of mean and 25th–75th percentile (box plots) values in the ten most common clinical CT examinations. The process was well conceived, describing data collection, analysis, presentation and dissemination back to hospitals. The team's success in a brief period of a few months should be celebrated, including the use of ICRP *Publication 135* (ICRP 2017) and other tools, and this approach may be applied by others. What is most impressive about this project group is that they have a deep understanding of project management and that each step is critical: the DRLs are iterative; they must be updated periodically and there is always opportunity for improvement (Bernardo *et al* 2021).

5.4. Summary of Committee 4 related presentations

Edith Villegas Garcia, Trieste AREA Science Park, Italy, emphasized 'Challenges in Radiation Protection for the Environment and Non-human Biota', and called for enlarging the approach adopted in ICRP *Publication 108* (ICRP 2008b). An ecosystem cannot be described completely by a simple collection of organisms, and the individual organism approach based on the human model is limited to ensure the protection of the ecosystems. The results of recent studies showing that low radiation doses can have a wide range of effects on bacteria, inducing potential resistance to antibiotics, were highlighted. From this perspective, it was mentioned that smaller organisms should not be ignored. The development of a collaborative database on the effects of different organisms was proposed, in order to guide decisions adapted to specific local ecosystems (Villegas Garcia 2021).

Mary Olson, Gender and Radiation Impact Project, USA, presented the results of a study from 2019 on 'Data Visualization and Gendered Questions in Radiation Protection'. The biological impact of ionizing radiation on the full human lifecycle was explored. The importance of considering the evolution of the person along her/his life instead of simplifying the approach with a reference person or population was emphasized. On this basis, the available data from atomic bomb survivors were analyzed, and the importance of considering gender differences over their lifetime was emphasized. Olson called for better integration of these differences into radiation regulation by centring the reference individual as a female under 6 years of age (Olson 2021).

Andy Mayall, UK Environment Agency, UK, *et al* discussed the need for 'Developing the System of Radiological Protection to Enhance its Contribution to the UN Sustainable Development Goals' in the context of the acceleration of change in global socio-economic challenges and environmental degradation. Adoption of an integrated approach to balancing social, environmental and economic risks and impacts was proposed. From this perspective, the UN Sustainable Development Goals were considered to be an ideal framework to review the three ICRP principles: justification, optimization, and limitation of radiation exposure (Mayall *et al* 2021).

Karla Petrová, Chair of the Head of European Radiation Protection Competent Authorities (HERCA), presented 'HERCA Suggestions for ICRP Future Work Areas', mentioning that these suggestions have to be considered as a preliminary list identified by the consultation of HERCA members. Four topics have been selected from this consultation: simplification of the System; justification and optimization and use of reference levels; radon; and communication. HERCA members are willing to cooperate with the ICRP, and to contribute to refinement of the System in the coming years, notably by producing specific HERCA documents and publications, and by organizing topical workshops (Petrová 2021).

Bernd Lorenz, Lorenz Consulting, Germany, called for significant evolution of the System emphasizing 'ICRP: it is Time for a Change, Now!' In terms of dose, the application of ICRP recommendations means that worldwide occupational exposure is <1 mSv yr^{-1}, which is far from dose limits. In this context, it was stated that the ICRP tends to ignore these results and overestimates the detrimental effects of ionizing radiation, notably with the new limit for the lens of the eye, the reference value for radon, and the new DCRLs. It was indicated that the ICRP recommendations adopted in ICRP *Publication 26* (ICRP 1977) have to be

reconsidered, and that the ICRP should state clearly that 'anybody' under the current radiological protection regime is safe. He recommended that the LNT hypothesis not be used (Lorenz 2021).

Carmel J Caruana, University of Malta, Malta, *et al* discussed the conditions for successful evolution of the system in 'ICRP Recommendations may be Fit for Purpose, but Without Adequate Human Resources, we Just Won't Get There'. The acute shortage of human resources to allow efficient practical implementation of the ICRP recommendations was highlighted. From this perspective, it was proposed that the education programmes for medical physics and radiation protection professions be combined. This innovative curriculum had been tested and found to be successful (Caruana and Pace 2021).

Jessica Callen-Kovtunova, University of Hannover, Germany, *et al* presented 'Making ICRP Recommendations 'Fit for Purpose' for the Response to a Nuclear or Radiological Emergency'. Based on a meta-analysis of more than 600 papers, estimates for excess early deaths due to implementation of protective actions following the FDNPP accident were reported, in comparison with hypothetical excess radiation-induced cancer. Better integration of these negative impacts in ICRP recommendations is required to ensure effective protection of people (Callen-Kovtunova and McKenna 2021).

Marcel Lips, World Nuclear Association, *et al* presented the position on 'Managing Ionising Radiation Risks: The Need for a Broader Context'. In the context of climate change, the need for the ICRP to adopt the 'all-hazard approach' was emphasized in order to avoid being focused too often on the local scale. In this context, careful consideration of the potential global impact of issues, such as the LNT hypothesis, education about the risk associated with low doses, over-conservatism, and the system of dose quantities, were recommended (Lips and de Ruvo 2021).

Greg Lamarre, OECD Nuclear Energy Association, *et al* presented the current reflection of the Committee on Radiological Protection and Public Health on 'Modernising Optimisation in Decision Making'. The key role of optimization in the implementation of the System was acknowledged, but the need to foster the development of a framework enabling the promotion of an inclusive and holistic decision-making process was highlighted. From this perspective, four pillars were mentioned that should be considered for practical implementation of the optimization principle: holistic or integrated protection; maximizing net benefit and the 'common good'; involving stakeholders and the need for proportionality. For this purpose, future work of the NEA Committee on Radiological Protection and Public Health will address three main issues: how policy and practice are developed in consultation with society; how policy and practice could be simplified; and how to integrate consideration of other policies and practices (Lamarre *et al* 2021).

Shigeru Kumazawa, Japan Atomic Energy Agency, Japan, *et al* presented an analysis on 'Quantitative Assessment of Risk Perception for Low Dose Risk'. The aim was to promote the adoption of a 'hybrid log-normal distribution', combining log and normal distributions notably when the annual dose approaches the dose limit. The model relies on developments performed in the 1980s, with application in different areas of radiation protection. Notably, the observations of characteristics of the model following the FDNPP accident for temporal and spatial attenuation of air dose rates, as well as in estimated individual-dose distributions of evacuated residents, were emphasized (Kumazawa *et al* 2021).

Hugh Wilkins, Radiation Consultancy Services, UK, presented a reflection on 'Radiation Protection Culture, Communication and Context'. The evolution of societal and cultural context was discussed, requiring the development of radiation protection culture to ensure that radiation risks are well understood by decision-makers and other stakeholders. From this perspective, organizational culture is a key component for developing good communication. The recent developments of the IAEA, WHO, IRPA and the International Organization for Medical Physics in this field were emphazised (Wilkins 2021).

Yoshiyuki Mizuno, Kyoto Women's University, Japan, presented the results of studies on 'Scientific Improvement on Social Understanding of Tritium, Ten Years After the Fukushima Nuclear Accident'. Starting from the difficult societal issue of tritium discharges into the ocean from FDNPP, a Monte-Carlo simulation was performed to reproduce the measured tritium concentration. The objective is to share the results with the public, including the fishermen in Fukushima. In addition, the possible separation of tritium using a centrifuge was investigated. The difficulties encountered in disseminating accurate and understandable information in the domain of radiation protection were mentioned (Mizuno 2021).

Catherine Taylor, Christie NHS Foundation Trust, UK, presented an approach to investigate 'Trust Self-assessed Radiation Safety Culture Across Sectors'. Based on the levels of radiation safety self-assessment adopted by the US National Council on Radiation Protection and Measurements, a comparative survey was performed between the medical sector and the nuclear sector in the UK, differentiating between three levels: task; process; and programme. The main components analyzed in the survey referred to accountability, openness and communication, continuous learning, and work process. The importance for the ICRP to incorporate aspects of communication and stakeholder engagement was emphazised (Taylor 2021).

5.5. Summary of ICRP task group presentations

Typically, each ICRP committee oversees a number of task groups on topics of relevance for pursuing the goals of the ICRP. In most cases, task groups are established to develop a draft report, which will, once approved by the corresponding committee(s) and the Main Commission, be put on the ICRP website for public consultation. At the Workshop, several task groups presented their work on topics that may be of importance in reviewing the System.

For quite some time, Task Group 36 on 'Radiation Dose to Patients in Diagnostic Nuclear Medicine' has been working, amongst other things, on the revision of ICRP *Publication 128* (ICRP 2015a) on 'Radiation Dose to Patients from Radiopharmaceuticals: a Compendium of Current Information Related to Frequently Used Substances', which is still based on the dosimetric system published in ICRP *Publication 60* (ICRP 1991). **Augusto Giussani**, Chair of Task Group 36, reported that this effort requires calculation of dose coefficients using, for example, the new ICRP adult and paediatric reference voxel phantoms from ICRP *Publication 110* (ICRP 2009a) and ICRP *Publication 143* (ICRP 2020), nuclear decay data from ICRP *Publication 107* (ICRP 2008a), the dosimetry methodology described in ICRP *Publication 103* (ICRP 2007), and fully compartmental models, if available, including updated biokinetic information (e.g. a revised compartmental model for the biokinetics and dosimetry for ^{18F}FDG or models including a more realistic description of the dynamic process of urinary excretion). Work may also include specific dosimetry for infants in the first year of life, and assessment of doses to subregions of organs or tissues in case of non-uniform distribution of administered radiopharmaceuticals. One aspect that Task Group 36 has discussed is even more fundamental; the use of effective dose in diagnostic nuclear medicine. To date, the calculation of effective dose is only performed for reference persons (averaged over age and sex), but in nuclear medicine, whole-body dose quantities may be useful for patients of only one sex or for patients with anatomical and physiological characteristics that are different to those of the reference persons (e.g. patients with thyroid examinations after ablation). Thus, applying the concept of effective dose to subgroups of the population, as well as reference persons, may be a step forward for many medical dosimetric applications, as highlighted by Clement *et al* (2021). In a way, ICRP *Publication 147* on 'Use of Dose Quantities in Radiological Protection' (ICRP 2021c) has already paved the way, and the work of Task Group 111 (see below) may provide further input along these lines (Giussani *et al* 2021).

Task Group 91 on 'Radiation Risk Inference at Low-dose and Low-dose-rate Exposure for Radiological Protection Purposes' addresses another question that is fundamental for the System: how to infer radiation risks for the System that were obtained from studies on the Japanese atomic bomb survivors at relatively high doses above approximately 100 mGy and at high-dose rates. One controversial example is DDREF, for which the ICRP has chosen a value of 2, and by which the radiation risks of solid cancers deduced for the atomic bomb survivors are reduced and then used in the System. DDREF was introduced in ICRP *Publication 60* (ICRP 1991) to combine inference at low doses and low-dose rates and confirmed in ICRP *Publication 103* (ICRP 2007). **Werner Rühm**, Chair of Task Group 91, mentioned that Task Group 91 has been reviewing the literature on subcellular and cellular studies, studies on experimental animals, and epidemiological studies on exposed human cohorts for several years. The results have been published in the open literature, and the relevant references are listed on the ICRP website of Task Group 91. Depending on the endpoint investigated, it appears that estimates for the dose-rate effectiveness factor and low-dose-effectiveness factor range between 1–3; narrowing it down to a more exact estimate is difficult (Rühm *et al* 2021a).

Nobuhiko Ban, Chair of Task Group 102, presented 'Radiation Detriment Calculation Methodology'. Radiation detriment is a concept developed by the ICRP to quantify the burden of stochastic effects from low-dose and/or low-dose-rate exposures to the human population. The aim of Task Group 102 is to provide a historical review of the detriment calculation methodology, to perform a selected sensitivity analysis to identify the parameters and calculation conditions that can be major sources of variation and uncertainty in the radiation detriment calculation, and to identify ways to improve the calculation of radiation detriment in the future. Although the current scheme for calculation of radiation detriment is well established, it needs to evolve to better reflect changes in population health statistics and progress in scientific understanding of radiation health effects. In this regard, some key parameters require updating, such as the reference population data and cancer severity. There is also room for improvement in cancer risk models based on the accumulation of recent epidemiological findings. Assumptions for the nominal risk calculation, including the LNT model, DDREF and the risk transfer scheme, must be examined in the light of the latest scientific findings. It is also desirable to review the risk estimate for heritable effects, taking recent studies into account. Another important aspect is handling the variation of cancer risk with sex and age. Consideration of non-cancer effects, specifically diseases of the circulatory system and cataracts is also needed. Finally, the importance of improving the comprehensibility of the detriment concept and the transparency of its calculation process is becoming increasingly important. The report of Task Group 102 is expected for publication in 2022.

A new question for radiological protection is raised by Task Group 110 on 'Radiological Protection in Veterinary Practice', which is how to protect animals within a revised radiological protection framework. **Jan Pentreath**, Emeritus Member of the Main Commission and Member of Task Group 110 emphasized that, in this context, protection of animals goes beyond just considering them as patients, but also includes consideration of animals being exposed for commercial reasons (e.g. CT scanning of sheep to determine their meat content or x-ray examinations of horses to attain a licence to race). How a society deals with radiological protection of the environment depends on ethical values, which can be grouped, for example, into the following categories: anthropocentric (or how the environment should be considered if it affects humans); biocentric (where individuals of species other than humans are considered); and eco-centric (which focuses on the ecosystem as a whole). For the protection of individual animals, there are practical issues regarding how to consider the three basic principles in radiological protection (which in one way or another reflect the ethical values mentioned). If individual animals are the target of protection, it is obvious that radiation-related effects and risks, as well as natural susceptibility to cancer, in these individual animals will become important. According to Jan Pentreath, the ICRP should first be 'clear about the scope of radiological protection' supported by a comprehensive ethic. Quantities and units should be developed further as, for example, equivalent and effective dose (expressed in Sv) cannot be used for any animal. Along these lines, the use of absorbed dose together with appropriate relative biological effectiveness (RBE) values may be an option [as proposed in ICRP *Publication 148* (ICRP 2021d)]. Reference models for animals of primary interest in veterinary practice may need to be developed, and dose estimates due to CT procedures on animals should be improved to support optimization. In summary, the paper calls for a revision of the current System and urges the ICRP to reconsider its scope based on a transparent ethical basis. It concludes by saying that 'The chance to do all of this within a revised ICRP set of Recommendations should not be missed' (Pentreath 2021).

The current System is based on estimations of radiation-related risks to a reference person. However, potential individualization of radiological protection is debated, and may inform future guidance, for example, in emergency situations, medical patient applications of ionizing radiation or in special settings, such as astronauts in space. Another example is radiotherapy for cancer, where severe normal tissue complications can be observed but not yet predicted in a small subset of the individuals treated. Understanding the underlying mechanistic basis can inform radiotherapy decision-making, improving tumour cure rates while avoiding acute severe complications. Consequently, Task Group 111 on 'Factors Governing the Individual Response of Humans to Ionising Radiation' is reviewing the current state of knowledge on variations in individual responses to radiation. **Simon Bouffler**, Chair of Task Group 111, mentioned in his presentation that the health effects reviewed by Task Group 111 include normal tissue reactions after radiotherapy, cancers, circulatory diseases, cognitive impairment and cataracts. Evidence considered includes clinical studies, epidemiological studies, experimental animal studies and cellular assays. Potential contributors to variation in response considered include genetic factors, epigenetic modifications, lifestyle factors, co-exposures and underlying health conditions. Should there be potential for prediction of individual responses, this may raise several questions, including which tests to be used (genetic, cellular, imaging), which subpopulations to be tested (medical, occupational) and which samples to take (blood, saliva, cell biopsy). Finally, how to deliver the outcomes—and the potential for further family member health risk screenings—to the affected individuals, their families, and their healthcare professionals, includes ethical considerations (Bouffler *et al* 2021).

Thierry Schneider, Chair of Task Group 114 on 'Reasonableness and Tolerability in the System of Radiological Protection', discussed the ongoing reflections of Task Group 114. This task group was created to review the historical and current perspectives of reasonableness and tolerability of radiation risk, to clarify and consolidate ICRP *Publication 103* (ICRP 2007) and to prepare the considerations and basis needed for development of future recommendations. The core ethical values on which the current System is based were emphasized: beneficence; non-maleficence; prudence; justice; and dignity [described in ICRP *Publication 138* (ICRP 2018)]. Tolerability is the degree to which something can be endured, while reasonableness means making rational, informed and impartial decisions that respect other views, goals and conflicting interests. In ICRP *Publication 60* (ICRP 1991), the border between tolerable and unacceptable risks (which is expressed as a dose limit) was defined by comparison with other common hazards occurring in both daily and working life. Task Group 114 emphazises that there is no single/universal value for the level of tolerable risk, as individuals and situations differ and that there might be a 'grey area' between tolerable and unacceptable. Therefore, a bottom-up approach including stakeholder involvement is preferred over a top-down approach. In this context, comparison between radiological and chemical risks might be useful to put these criteria into perspective. For a specific situation, even if a tolerable risk has been identified, the interplay between tolerability and reasonableness is complicated as it does not only include the level of risk but also includes

ethical values and societal and contextual considerations. This is also reflected in the ALARA principle. The current view of Task Group 114, as developed in collaboration with various international organizations, is that reasonableness refers to good judgement, fairness, practicability, moderateness and appropriateness. A reasonable exposure might be identified by looking for an appropriate level of protection, maximizing the well-being of everybody by developing compromises, integrating ethical issues and considering risk perception. Task Group 114 has developed a preliminary approach relying on the three Rs: 'relationships', 'rationale' and 'resources'. As next steps, Task Group 114 will further investigate the application of the concept of tolerability; refine the three Rs of reasonableness; and apply the concepts of tolerability and reasonableness for protection of the environment, medical exposures and potential exposures (Schneider *et al* 2021).

The three Rs of reasonableness mentioned above were further described in another presentation of Task Group 114 given by **Nicole Martinez**. The goal was to develop a tool to help support a structured, transparent reflection on the factors that make up 'reasonable', which is neither new nor easy. The tool should be easy to understand and use, integrate common themes, and be broadly applicable and memorable. Consequently, the following three categories relevant for reasonableness (the three R's) were identified: (a) 'relationships', which involves stakeholder engagement (considering risk perception and co-expertise), transparency (acknowledging the role of communication in building trust) and empathy (for understanding the perspective(s) of others); (b) 'rationale', which includes technical (assessing and discussing risks, benefits and uncertainties), contextual (understanding and incorporating prevailing circumstances) and ethical (doing the right thing) contexts; and (c) 'resources', which includes technological (using appropriate methods, techniques and technologies), financial (including responsible spending) and temporal (considering timescale, duration and working hour distribution) aspects. For each of these categories, Task Group 114 has drafted guidelines in the form of handouts and procedural checklists (Martinez *et al* 2021).

Task Group 115 on 'Risk and Dose Assessment for Radiological Protection of Astronauts' was established in 2019, motivated by a request from the International Systems Maturation Team involving space agencies involved in the International Space Station. The Chair of Task Group 115, **Werner Rühm**, mentioned that the aim of the task group is to examine effects that may impact crew health and mission success (including effects on the central nervous system, cardiovascular disease, lens opacification) and to develop a common health risk assessment framework and recommendations on exposure limits for exploration-class human spaceflight missions. This work will build on ICRP *Publication 123* (ICRP 2013) on 'Risk and Dose Assessment for Radiological Protection of Astronauts'. To date, Task Group 115 has defined two example missions: one cislunar and one lunar surface mission. Exposures will be estimated from galactic cosmic radiation and from a solar particle event, and corresponding radiation-related risks will be calculated following procedures used by various space agencies. Emphasis will be placed on the available metrics to calculate cancer risks, and on issues related to RBE and radiation quality factors (building on work undertaken by Task Group 118—see below) to be used for the radiation field in space. The long-term goal of Task Group 115 is to work on how the principles of radiological protection can be applied to the space environment, mirroring ICRP *Publication 132* (ICRP 2016) on 'Radiological Protection from Cosmic Radiation in Aviation' (Rühm *et al* 2021b).

Gayle Woloschak, Chair of Task Group 118 on 'Building Upon ICRP 92 on RBE, Radiation Weighting Factor and Q Factor' discussed a literature review that the task group has undertaken including publications from 2001–2021 to cover work undertaken since ICRP *Publication 92* (ICRP 2003b). More than 300 papers on RBE of various radiation types have been identified that could be of relevance. Many studies looked at RBE at proton therapy facilities, and, in some cases, also included boron neutron capture therapy and carbon therapy. A number of animal studies have been undertaken on protons and heavy ions involving zebrafish, rats and mice, many of them to support the National Aeronautics and Space Administration's work to learn about the radiation field in space. Modelling papers used different approaches to examine neutron RBE with energy and examined RBE in the spread-out Bragg peak of protons and carbon ions, including cellular and animal endpoints. Numerous *in vitro* studies have been performed, including, for example, DNA damage or cell survival and some *ex vivo* studies including human cells exposed *in vitro*. Some literature was also found on plant studies (involving, for example, onion root tips), all undertaken in the laboratory. Human epidemiological studies included studies on the RBE of neutrons in atomic bomb survivors, and of alpha particles in French uranium miners and Russian plutonium workers. In the future, Task Group 118 will consider the effect of dose rate on RBE, differences in and out of the Bragg peak, the importance of reference radiation choice for RBE, secondary cancers as an endpoint, and the contribution of neutrons to the dosimetry of the atomic bomb survivor work (Woloschak *et al* 2021).

Very recently, the ICRP has launched Task Group 119 on the 'Effects of Ionising Radiation on Diseases of the Circulatory System (DCS) and their Consideration in the System of Radiological Protection', chaired by **Tamara Azizova**. While it has been known for quite some time that therapeutic doses of ionizing radiation,

such as fractionated high doses from radiotherapy for the treatment of intrathoracic malignancies, can cause damage to the heart and blood vessels (e.g. carotid and coronary arteries) in humans, and induce an increase in the incidence of DCS and mortality one or two decades after exposure, it was only more recently that evidence appeared for increased risks of DCS at doses as low as several hundred mGy. In ICRP *Publication 118* (ICRP 2012), a threshold of approximately 0.5 Gy for acute and fractionated/prolonged exposures to the brain and heart was proposed for the purpose of radiological protection, and DCS was classified as a tissue reaction. However, challenges remain regarding the shape of the DCS dose response, its classification as a tissue reaction, and the associated underlying biological mechanisms. Consequently, the objectives of Task Group 119 are to review the recent scientific literature on related radio-epidemiological and radiobiological studies of DCS, to provide advice on the radiation-dose response for DCS, to provide advice on dose-rate dependence and radiation-quality dependence on the risk of DCS and to provide advice on how to reflect current knowledge of radiogenic DCS in the System. Task Group 119 activities will be performed in close collaboration with an UNSCEAR Expert Group on a similar topic (Azizova *et al* 2021).

6. Conclusion

The ICRP has recently launched a process to review the System and develop a successor to ICRP *Publication 103* (ICRP 2017). The ICRP considers this to be an effort that should be made jointly with all of the ICRP's international stakeholder community, in a collaborative spirit, allowing for accessible, open, transparent and meaningful participation.

The Workshop on the Future of Radiological Protection, organized by the ICRP from 14 October–3 November 2021, offered participants from all over the world the opportunity to engage in this process and share their ideas. Registration fees were flexible, including a zero-cost option to ensure there was no financial barrier to participation. In total, almost 1500 registered participants were able to listen to 20 live-streamed presentations and 43 on-demand presentations, and engage in questions and answers with the presenters. Between 500 and 800 participants watched each of the four live sessions in real time, while the on-demand presentations were visited more than 7000 times.

Among the many issues discussed, presentations covered the scientific basis of the System (including both radiation-related effects and dosimetry), the application of radiation technologies, the communication of the benefits/risks of these technologies, the role of ethics in decision-making, and the uncertainties of each (effects, dosimetry, and the benefits/risks of technological uses). Several presentations also addressed aspects of the paper on 'Areas of Research to Support the System of Radiological Protection' (Laurier *et al* 2021).

Other presentations dealt with the concept of the System and how it could be improved. Furthermore, the need for the System to be practical and understandable in order to be applied was often stressed. Communication, education and training are tied directly to this. Some of the more fundamental considerations included the role of the ICRP as an international organization; its interaction with other international organizations (scientific institutions, regulators, practitioners, etc); and its engagement, with stakeholders including workers, members of the public, and patients (i.e. society as a whole). A number of these issues were also mentioned in the paper on 'Keeping the ICRP Recommendations Fit for Purpose' (Clement *et al* 2021).

The digital format of the Workshop was developed because the coronavirus disease 2019 pandemic did not allow for the organization of large face-to-face meetings in 2021. Although the platform used for the Workshop supported direct interaction between the participants (including a chat function and allowing for video calls) and the speakers through a question and answer option, this could not fully replace direct face-to-face interaction. Nevertheless, with hindsight, the format used for the Workshop is considered to have been successful since it allowed the ICRP to reach a much larger audience at lower cost (because travel costs were avoided) than would have been possible with a face-to-face meeting, and had the additional benefit of a lower carbon footprint.

Based on this experience, the ICRP is considering the use of additional open digital formats in the future. This may include digital webinars where newly published ICRP reports are presented and explained, and digital workshops focusing on ICRP task groups where specific topics can be discussed. In the future, the Main Commission also envisages organizing digital workshops such as those described here in the years between the biennial ICRP symposia. At the next ICRP symposium, due to be held in Vancouver, Canada, from 3–7 November 2022, the topic of revision of the current System will be discussed further, based on the feedback and findings obtained at the Workshop described in this paper. The Main Commission is grateful to all those who shared their thoughts at the Workshop, and considers the reflections expressed to be very constructive and helpful for the process of reviewing and refining the current System.

Acknowledgments

The German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection kindly supported the preparation of a summary of the ICRP Digital Workshop on the Future of Radiological Protection under Contract #3620I02264.

ORCID iDs

W Rühm https://orcid.org/0000-0002-6354-7359
C Clement https://orcid.org/0000-0003-1343-2585
D Cool https://orcid.org/0000-0003-4105-0242
D Laurier https://orcid.org/0000-0003-1432-4738
F Bochud https://orcid.org/0000-0003-2076-0296
K Applegate https://orcid.org/0000-0001-7716-1636
T Schneider https://orcid.org/0000-0003-0094-5293
S Bouffler https://orcid.org/0000-0003-1883-919X
K Cho https://orcid.org/0000-0002-7723-6973
G Hirth https://orcid.org/0000-0002-5478-1127
M Kai https://orcid.org/0000-0001-7812-727X
S Romanov https://orcid.org/0000-0002-8642-3850
A Wojcik https://orcid.org/0000-0002-3951-774X

References

Andresz S, Vermeersch F and Stritt N 2021 Application of the graded approach for the radiation protection of workers: examples and reflexions from European ALARA Networks *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=513) (Accessed 18 March 2022)

Azizova T *et al* 2021 TG 119: effects of ionising radiation on diseases of the circulatory system and their consideration in the system of radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=523) (Accessed 18 March 2022)

Ban N *et al* 2021 Possible improvements of methodology for calculating radiation detriment in the future *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=512) (Accessed 18 March 2022)

Bando M, Suzuki K, Tsunoyama Y and Toki H 2021 Unified understanding of biological effects caused by radiation: overcoming LQM difficulties *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=557) (Accessed 18 March 2022)

BenDriss H, El Mahjoub C, El Bakkali J and Doudouh A 2021 InterDosi-based Monte-Carlo Assessment of S-values on a voxel-based crab phantom for Cs-137, Te-132 and Co-58 *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=540) (Accessed 18 March 2022)

Bernardo M, Morgado F, Tapajós J, Henschel R, Paulo G and Costa P 2021 Strategies to implement dose reference level in tomography in Brazil: preliminary analysis *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=556) (Accessed 18 March 2022)

Bouffler S *et al* 2021 TG 111: factors governing the individual response of humans to ionising radiation *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=518) (Accessed 18 March 2022)

Burtt J J *et al* 2021 Advancing the adverse outcome pathway (AOP) in radiation research: an international horizon-style exercise *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=526) (Accessed 18 March 2022)

Callen-Kovtunova J and McKenna T 2021 Making ICRP recommendations 'fit for purpose' for the response to a nuclear or radiological emergency *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=543) (Accessed 18 March 2022)

Caruana C J and Pace E 2021 ICRP recommendations may be fit for purpose, but without adequate human resources, we just won't get there *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=536) (Accessed 18 March 2022)

Castillo A, Mendoza J, Roas N and Somarriba F 2021 Calibration of a dosimetric system in $H_p(3)$ using a cylindrical phantom *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=529) (Accessed 18 March 2022)

Chambers D 2021 Updating the ICRP'S recommendations: a practitioner's perspective *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=514) (Accessed 18 March 2022)

Clement C *et al* 2021 Keeping the ICRP recommendations fit for purpose *J. Radiol. Prot.* **41** 1390

Coates R 2021 The need to review low-dose decision-making in radiation protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=513) (Accessed 18 March 2022)

Coates R and Czarwinski R 2018 IRPA consultation: is the system of protection 'fit for purpose' and can it be readily communicated? Views of the radiation protection professionals *J. Radiol. Prot.* **38** 440

Cromnier N, Almén A, Cederlund T, Hofvander P, Johansson J and Wiklund Å 2021 The need for bridging the gaps between theory and practice: an authority's perspective in some identified areas *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=514) (Accessed 18 March 2022)

Cruz A R P and Jornada T S 2021 Influence of different operating modes (high, normal and low) and FOV sizes on air kerma rate in different interventional radiology equipment *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=539) (Accessed 18 March 2022)

Filimonova F, Shevchenko L, Filimonov A, Makarchuk V, Saburova A and Koryakin S 2021 A promising concept for the development of means for the prevention of radiation pathologies *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=524) (Accessed 18 March 2022)

García-Fernández G *et al* 2021 Impact of new developments in the commissioning of operational radiation protection in compact proton therapy centres (CPTC) *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=538) (Accessed 18 March 2022)

Garnier-Laplace J *et al* 2021 Reducing uncertainties in low dose/low dose rate health risks requires international networking in research implementation and its communication to stakeholders *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=512) (Accessed 18 March 2022)

Giussani A, Mattsson S, Nosske D, Hasono M and Andersson M 2021 TG 36: the revision of dose coefficients in diagnostic nuclear medicine *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=515) (Accessed 18 March 2022)

Gomina M, Kolo M T, Olarinoye O I, Bashir M, Suleiman I K and Gene A S 2021 Assessment of non-human biota dose at the El Amin University proposed site, Minna, Nigeria *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=527) (Accessed 18 March 2022)

González A J 2021 Prospects on the ICRP paradigm for radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=513) (Accessed 18 March 2022)

Grambow B 2021 Radiological risk in the global burden of disease *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=553) (Accessed 18 March 2022)

Hamaoka Y 2021 LNT model is not an 'assumption': re-analysis of epidemiological data empirically supports LNT *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=542) (Accessed 18 March 2022)

Higley K A, Hargraves J T, Newmyer J, Kustka S M, Elmore III B F and Stricker A J 2021 What should be the role of higher education in the future of radiological protection? *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=511) (Accessed 18 March 2022)

ICRP 1977 Recommendations of the ICRP. ICRP Publication 26 *Ann. ICRP* **1**

ICRP 1991 1990 recommendations of the international commission on radiological protection. ICRP Publication 60 *Ann. ICRP* **21**

ICRP 2003a A framework for assessing the impact of ionising radiation on non-human species. ICRP Publication 91 *Ann. ICRP* **33**

ICRP 2003b Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (w_R). ICRP Publication 92 *Ann. ICRP* **33**

ICRP 2007 The 2007 recommendations of the International Commission on Radiological Protection. ICRP Publication 103 *Ann. ICRP* **37**

ICRP 2008a Nuclear decay data for dosimetric calculations. ICRP Publication 107 *Ann. ICRP* **38**

ICRP 2008b Environmental protection—the concept and use of reference animals and plants. ICRP Publication 108 *Ann. ICRP* **38**

ICRP 2009a Adult reference computational phantoms. ICRP Publication 110 *Ann. ICRP* **39**

ICRP 2012 ICRP statement on tissue reactions/early and late effects of radiation in normal tissues and organs—threshold doses for tissue reactions in a radiation protection context. ICRP Publication 118 *Ann. ICRP* **41**

ICRP 2013 Assessment of radiation exposure of astronauts in space. ICRP Publication 123 *Ann. ICRP* **42**

ICRP 2014 Radiological protection in ion beam radiotherapy. ICRP Publication 127 *Ann. ICRP* **43**

ICRP 2015a Radiation dose to patients from radiopharmaceuticals: a compendium of current information related to frequently used substances. ICRP Publication 128 *Ann. ICRP* **44**

ICRP 2016 Radiological protection from cosmic radiation in aviation. ICRP Publication 132 *Ann. ICRP* **45**

ICRP 2017 Diagnostic reference levels in medical imaging. ICRP Publication 135 *Ann. ICRP* **46**

ICRP 2018 Ethical foundations of the system of radiological protection. ICRP Publication 138 *Ann. ICRP* **47**

ICRP 2020 Paediatric computational reference phantoms. ICRP Publication 143 *Ann. ICRP* **49**

ICRP 2021a Cancer risk from exposure to plutonium and uranium. ICRP Publication 150 *Ann. ICRP* **50**

ICRP 2021b *Summary of the ICRP Main Commission Meeting* (*Frankfurt, Germany, 15–18 November 2021*) (available at: https://icrp.org/admin/Summary%20of%20November%202021%20Main%20Commission%20Meeting.pdf) (Accessed 18 March 2022)

ICRP 2021c Use of dose quantities in radiological protection. ICRP Publication 147 *Ann. ICRP* **50**

ICRP 2021d Radiation weighting for reference animals and plants. ICRP Publication 148 *Ann. ICRP* **50**

IRPA 2021 *IRPA Perspective on 'Reasonableness' in the Optimisation of Radiation Protection* (available at: https://irpa.net/docs/IRPA%20Perspective.pdf) (Accessed 18 March 2022)

Janžekovič H 2021 ICRP Publication 103 and authorization and inspection processes *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=514) (Accessed 18 March 2022)

Jeffries C 2021 Does the system of radiological protection require science to the nth degree to be fit for purpose? *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=534) (Accessed 18 March 2022)

Johnston P 2021 Working together on development of international guidance documents in radiation safety *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=511) (Accessed 18 March 2022)

Joseph D Z, Nkubli F, Chukwuemeka N C, Agwu K K, Egbe N and Okeji M C 2021 Education and training in radiation protection: bridging the gap to keep ICRP recommendations fit for purpose *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=514) (Accessed 18 March 2022)

Kumazawa S, Toyota N and Katoh K 2021 Quantitative assessment of risk perception for low dose risk *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=548) (Accessed 18 March 2022)

Lamarre G *et al* 2021 Modernising optimisation in decision making *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=545) (Accessed 18 March 2022)

Laurier D, Rühm W, Paquet F, Applegate K, Cool D and Clement C 2021 International commission on radiological protection (ICRP), 2021. Areas of research to support the system of radiological protection *Radiat. Environ. Biophys.* **60** 519–30

Lecomte J-F 2021 Summary of the third SFRP/IRPA workshop on the application of the concept of tolerability *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=513) (Accessed 18 March 2022)

Lee S-C 2021 A study for dose impact of MCR operators in nuclear power plants under ICRP 30 and ICRP 60 *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=525) (Accessed 18 March 2022)

Lips M and de Ruvo A 2021 Managing ionising radiation risks: the need for a broader context *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=544) (Accessed 18 March 2022)

Lorenz B 2021 ICRP: it is time for a change, now! *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=537) (Accessed 18 March 2022)

Magnússon S, LeGuen B and Chapple C-L 2021 IRPA perspective on the review of the system of radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=511) (Accessed 18 March 2022)

Malone J 2021 ICRP and a century of governance and ethics for radiation protection in medicine *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=514) (Accessed 18 March 2022)

Martinez M, Wieder J and Schneider T 2021 TG114: the three R's of reasonable: relationships, rationale, and resources *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=520) (Accessed 18 March 2022)

Martinez N and Zölzer F 2021 Consistency and Complementarity of ethical values across the system and practice of radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=513) (Accessed 18 March 2022)

Mathews J D 2021 Revisiting next generation effects of ionizing radiation *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=512) (Accessed 18 March 2022)

Mayall A, Stackhouse A, Dowds C, Wakefield A and Orr P 2021 Developing the system of radiological protection to enhance its contribution to the UN sustainable development goals *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=533) (Accessed 18 March 2022)

Mizuno Y 2021 Scientific improvement on social understanding of tritium, ten years after the Fukushima nuclear accident *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=554) (Accessed 18 March 2022)

Moores M and Mattsson S 2021 Comments on the system of radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=531) (Accessed 18 March 2022)

Nadareishvili D, Gedevanishvili V, Alkhanishvili Z, Jariashvili K, Kiparoidze S and Maisuradze A 2021 Attitudes of staff involved in dental radiological procedures in Georgia towards radiation protection and safety: a questionnaire-based study *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=528) (Accessed 18 March 2022)

Ninsiima L, Boadu M, Inkoom S and Botwe B 2021 Optimization of dose for adult chest computed tomography examinations: a phantom study *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=546) (Accessed 18 March 2022)

Nkubli F B, Joseph D Z, Moi A S, Abubakar M, Nwobi C and Nzotta C C 2021 Keeping the ICRP recommendations fit for purpose and the need for a global north–south collaboration *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=511) (Accessed 18 March 2022)

Olson M 2021 Data visualization and gendered questions in radiation protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=532) (Accessed 18 March 2022)

Pentreath J R 2021 TG 110: protecting animals within a revised radiological protection framework *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=517) (Accessed 18 March 2022)

Petrová K 2021 HERCA suggestions for ICRP future work areas *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=535) (Accessed 18 March 2022)

Rühm W *et al* 2021a TG 91: radiation risk inference at low-dose and low-dose-rate exposure for radiological protection purposes *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=516) (Accessed 18 March 2022)

Rühm W *et al* 2021b TG 115: risk and dose assessment for radiological protection of astronauts *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=521) (Accessed 18 March 2022)

Rühm W 2021 Review & revision of the system of radiological protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=511) (Accessed 18 March 2022)

Sasaki M, Tomita M, Sugiyama D, Hattori T and Iwasaki T 2021 Issues concerning the carcinogenesis risk and implementation of the system of RP *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=541) (Accessed 18 March 2022)

Schneider T *et al* 2021 TG 114: reasonableness and tolerability in the system of radiological protection. ICRP TG114 on-going reflections *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=519) (Accessed 18 March 2022)

Taylor C 2021 Self-assessed radiation safety culture across sectors *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=555) (Accessed 18 March 2022)

Tomita M, Fujimichi Y and Uchinomiya K 2021 Radiation-induced stem cell competition and dose-rate effect *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=552) (Accessed 18 March 2022)

Trott K 2021 What is needed to keep ICRP recommendations fit for future? *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=512) (Accessed 18 March 2022)

Tsunoyama Y, Toki H and Bando M 2021 A proposal for the application of mathematical models that accurately approximate measured data to radiation protection *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=512) (Accessed 18 March 2022)

Vaillant L, Kai M and Hauptmann M 2021 Radiation detriment calculation methodology: review of current non-radiation-related parameters and perspectives *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=549) (Accessed 18 March 2022)

Vanhavere F 2021 Personal online dosimetry using computational methods: the PODIUM project and the future of active dosimetry *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=547) (Accessed 18 March 2022)

Vassileva J and Holmberg O 2021 Radiation protection perspective to recurrent medical radiological imaging *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=551) (Accessed 18 March 2022)

Villegas Garcia E 2021 Challenges in radiation protection for the environment and non-human biota *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=530) (Accessed 18 March 2022)

Wilkins H 2021 Radiation protection culture, communication and context *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=550) (Accessed 18 March 2022)

Woloschak G *et al* 2021 TG 118: building upon ICRP Publication 92 on RBE, radiation weighting factor and Q factor *ICRP Digital Workshop on the System of Radiological Protection* (*14 October–3 November 2021*) (available at: https://icrp.org/page.asp?id=522) (Accessed 18 March 2022)