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Reference N°	Creation Date	
SCK CEN/41873928	2021-01-22	
Alternative Reference N°	Revision	Version
N/A	1.0	1
ISC	Revision Status	
Public	Approved	

EJP-CONCERT D3.7 Second joint roadmap for radiation protection research.pdf

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Approval information for current revision*		
Name	**Outcome**	**Date**
Nele Horemans	Approved	2021-01-25

Change log*				
Revision	**Version**	**Status**	**Date**	**Description of change**
1.0	1	Approved	2021-01-22	

Ref. Ares(2020)808823 - 07/02/2020

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 662287.

EJP-CONCERT

European Joint Programme for the Integration of Radiation Protection Research

H2020 – 662287

D3.7 Second joint roadmap for radiation protection research*

*__Draft__ for review by CONCERT, the radiation protection research platforms and stakeholders

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Disclaimers:

a) The information and views set out in this report are those of the author(s). The European Commission may not be held responsible for the use that may be made of the information contained therein.

b) The current version of the joint roadmap is the *work of the joint roadmap working group* consisting of the above mentioned authors and co-authors. This version will be presented for review to the full membership of CONCERT, the different platforms, stakeholders in radiation protection and to end users (national =final representatives and the EC) in the first months of 2020. Considering the comments received, ***a revised = final version*** endorsed by CONCERT consortium will be prepared by **end of May 2020**.

Work package / Task	WP3	T3.3
Deliverable nature:	Report (Draft)	
Dissemination level: (Confidentiality)	Public	
Contractual delivery date:	31 December 2019 (M55)	
Actual delivery date:	8 January 2020 (M56)	
Version:	1	
Total number of pages:	57 + annexes	
Keywords:	Joint Roadmap, radiation protection, low dose risk, radioecology, nuclear and radiological emergency preparedness and response, dosimetry, medical radiation	
Approved by the coordinator:	M57	
Submitted to EC by the coordinator:	M57	

Abstract

This Joint Roadmap for radiation protection research is established under WP3 of the H2020 CONCERT European Joint Programme by a working group including representatives of the six radiation protection research platforms and specific CONCERT Programme Owners and Programme Managers.

Within Europe, many organisations and associations have important experience in radiation protection research. To face effectively future challenges and make efficient use of resources (at both national and European levels), we believe that a common and shared vision for radiation protection research is required – the Joint Roadmap provides this vision.

Future challenges can be addressed and answered if we have a clear path forward both in terms of a common programme (R&D and implementation) and required capacities (maintaining and building future workforce and infrastructure) clearly set out in the Joint Roadmap, presented within this deliverable. Additionally, we need to develop the structure and governance to manage a European radiation protection R&D programme, which is another expected outcome from CONCERT.

This Joint Roadmap defines priority areas and strategic objectives for mutual cooperation and provides a vision and role for a European radiation protection research programme to 2030 and beyond.

The Joint Roadmap presents a view of the research challenges in the context of existing and potential exposure scenarios, relevant from societal and radiation protection points of view. Within these research challenges, the joint roadmap presents '*game changers'*, defined as research issues that, when successfully resolved, have the potential to impact substantially and strengthen the system and/or practice of radiation protection for man and/or the environment through 1) significantly improving the evidence base, 2) developing principles and recommendations, 3) developing standards based on the recommendations and 4) improving practice.

Within the first half of 2020, this Joint Roadmap, and the associated *game changers* will be presented for consultation to the research communities, end users, decision makers and other stakeholders for evaluation and further evolution of priorities. Taking into account this final consultation round within the time frame of CONCERT and after approval by the CONCERT consortium, a final version of the joint roadmap with strengthened priority setting will be published mid-2020 which will be proposed as basis of future R&D, resource and financial support planning. Within the course of 2020 the joint roadmap will also be presented within and beyond Europe, aiming to build cooperation and collaboration between research communities on a global scale. The joint roadmap is a living document that will need to be updated on a regular basis, considering advances and developments that affect the research needs.

The implementation and timescale of the joint roadmap will depend on the availability of human, infrastructural and financial resources in the Member States, on the EU level and progress with wider global integration. The availability of a coordinated funding mechanism would benefit the implementation of the roadmap and realisation of its goals. A long-term commitment by Europe of this sort would allow for the implementation and realisation of this ambitious radiation protection research roadmap shaped by societal challenges.

CONTENT

1. Foreword

Since the HLEG report[1] about ten years ago, a remarkable reorganisation of the European radiation protection research landscape has taken place. The report on European Low Dose Risk Research subsequently led to the establishment of the MELODI platform, an association of European institutes committed to low dose risk research and openly sharing their vision and Strategic Research Agenda with the multidisciplinary scientific community. The mode of operation turned out to be very successful and several other research platforms in radiation protection were set up soon thereafter, addressing research on radioecology (ALLIANCE), nuclear and radiological emergency preparedness and response (NERIS) and medical radiation (EURAMED). The European Dosimetry Group (EURADOS) that was founded in the 1980´s as an expert group, also prepared an ambitious SRA. The newly established SHARE platform has further consolidated the expertise in social sciences and humanities in radiation protection research.

All platforms have developed specific SRAs in their field of activity and continue working on specific roadmaps. While the individual platforms have brought together European scientists and consolidated their research strategies, there is also an increased collaboration between the radiation protection platforms within the integrative work packages of CONCERT to develop priorities and the joint roadmap. Also the research projects recently funded require the collaboration of scientists from the different platforms.

A Memorandum of Understanding (MoU) was established between these platforms confirming an umbrella structure (MEENAS) to further foster and enhance European radiation protection research and support collaboration. The implementation of a Joint Roadmap for Radiation Protection Research is a key element in this MoU.

The scope of research envisaged in the joint roadmap is in the context of various existing and potential exposure scenarios, relevant from societal and radiation protection point of view. The key aim is to provide answers to open questions related to the exposure of humans and the environment, for example to reduce uncertainties in risk assessment and to provide sound, applicable solutions for risk management. Research and development are needed in every step of the radiation protection knowledge updating process, ranging from underpinning science to principles, recommendations, standards and practice, represented at the international level by UNSCEAR, ICRP, IAEA/ISO/EC and IRPA, respectively (Figure 1). This joint roadmap aims to provide an instrument designed to support the updating of knowledge. In other words, implementation of the joint roadmap for radiation protection research should provide the knowledge and expertise needed to improve the radiation protection system and its execution over the coming decades.

This report describes the joint roadmap for research on radiation protection in Europe. The Joint Roadmap is prepared within the European scope but will be shared on a global scale to stakeholders, researchers and research funding institutions, to assess the possibility of research programming and co-funding, research cooperation and collaborations beyond Europe. This document is meant to be a living document, to be updated regularly to consider advances in the state of the art and future societal challenges.

[1] https://cordis.europa.eu/docs/publications/1070/107087891-6_en.pdf

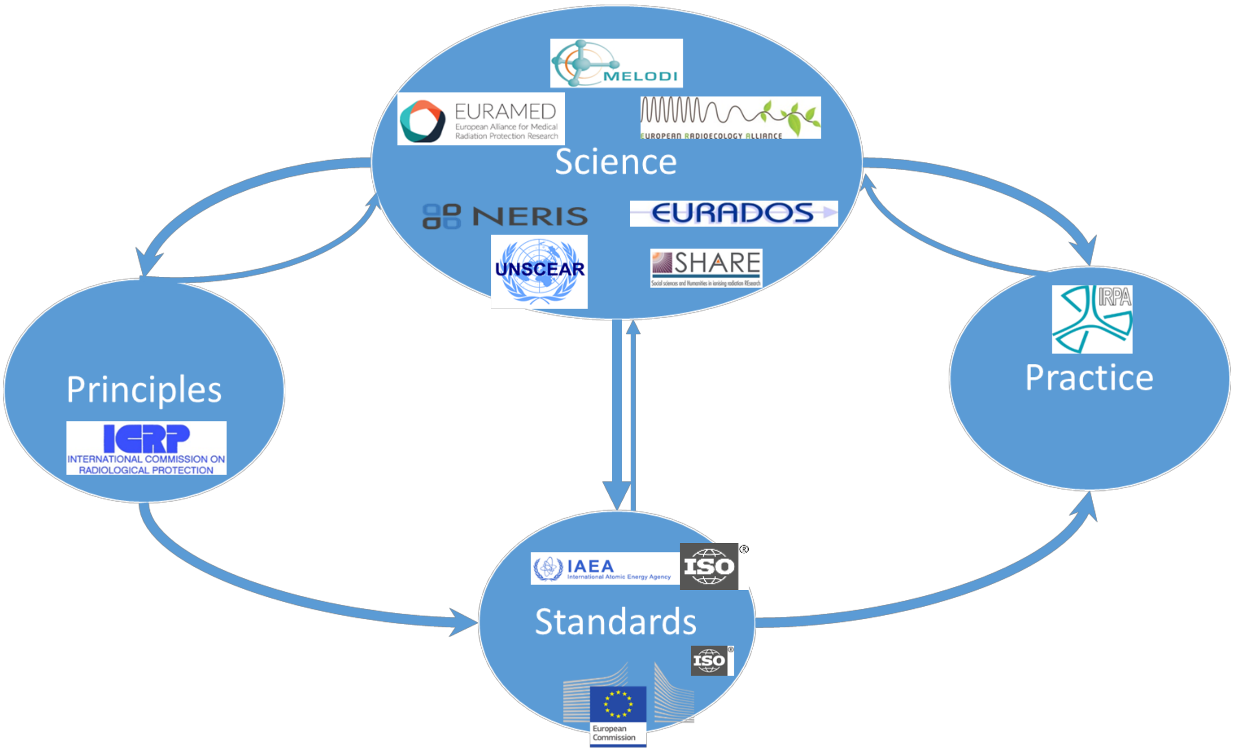


Figure 1. Role of science in the process of updating and implementing the radiation protection system. Research and development are needed in this process, ranging from underpinning science to principles/recommendations, standards and practice.

Implementation of the joint roadmap will have impact on radiation protection of humans and the environment in many ways (Figure 2). First, by consolidating our scientific knowledge the joint roadmap will support the implementation of the European Basic Safety Standards, to help cope with the new requirements and harmonize the practices throughout Europe. The joint roadmap addresses both human protection and protection of the environment. The holistic approach covers both risk assessment and risk management, as well as development of tools, methods and best practices to cope with the issues related to radiation exposure, thus making a major impact on society. Research is needed for risk prediction in specific situations and for foresight, to anticipate potential exposures. New knowledge will contribute to evidence-based recommendations at international level and informed risk communication. Research on risk management will help on risk prevention, improve the resilience of societies for emergencies, help to set up action plans and work on the mitigation and remediation. Guidelines, recommendations and regulations are needed, along with good practices and reliable methods for field and laboratory work. A graded approach in risk management is needed and research will help in putting exposures and risks in perspective. Technological development comes up with new standards, technological innovations and improved capabilities.

The research foreseen and the derived recommendations will enable consolidated, harmonised and robust decision making in the field of radiation protection throughout Europe and beyond.

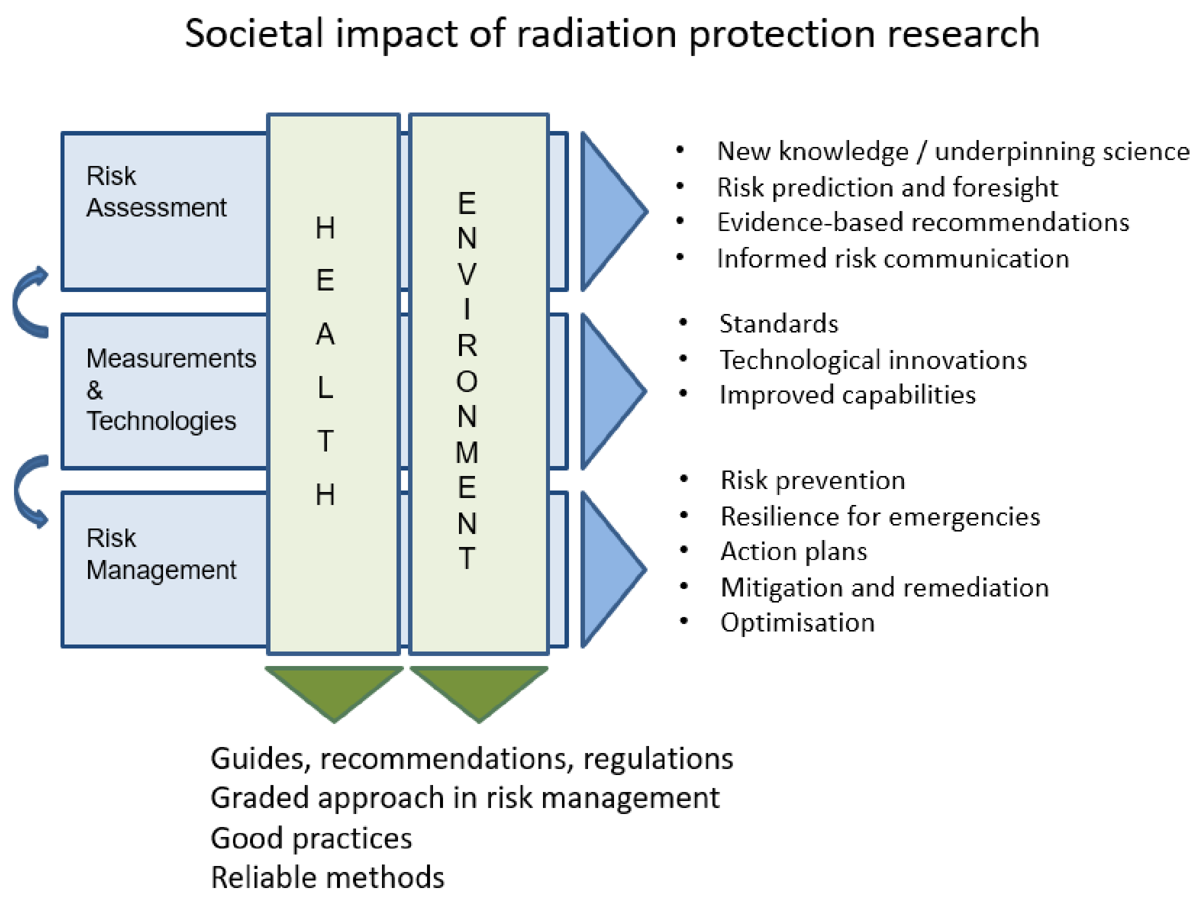


Figure 2. The research ecosystem ranges from basic research to applied research and from risk assessment to risk management. The societal impact from radiation protection research will result into improved risk assessment and risk management, both supported by technological innovations. The regulators and competent authorities on protection of health and the environment rely on the output from the research and technological development processes at all levels.

2. Scope of the research presented in the joint roadmap: exposure contexts and scenario groups

The goal of the joint roadmap is to identify the research needs and the development of tools that will further optimize the existing radiation protection system and advance radiation protection, considering the societal needs and concerns, and to plan such research. Implementation of the joint roadmap for radiation protection research will deliver the knowledge and expertise needed to further improve the radiation protection system over the next decades.

The scope of research planned in the joint roadmap is to provide information and tools for radiation protection in the context of various existing and potential exposure scenarios, driven by a societal and radiation protection point of view.

In this Chapter 2 we present the potential exposures of humans and the environment in a two-dimensional approach, with on one side **RP (radiation protection)** contexts resulting from man-made or natural sources of exposures, and on the other side **exposure scenarios** that may result from planned, existing or emergency situations. A graphical representation of this two-dimensional approach is available in Table 1.

2.1. Radiation protection contexts

Exposures to ionising radiation for which radiation protection may be required can be grouped in the four following contexts, from which the first three result from human activities, whereas the last one is inherent to the natural environment on earth, in the atmosphere and in space.

I. **Human activities related to medical therapy and diagnosis using radionuclides and X rays, electrons, protons or ions:** medical exposure of patients and the consequent exposure of personnel and the public due to medical procedures, the production and manipulation of sources/radiopharmaceuticals and related radioactive waste management.

II. **Human activities related to nuclear energy applications and other industrial applications of ionising radiation not related to medical applications**
   a. Installations from the nuclear fuel cycle: uranium mining and milling, fuel preparation, exploitations such as energy production in nuclear power plants, spent fuel reprocessing, waste management and decommissioning, research reactors and fusion research. Site contamination due to normal operation, incidents, accidents potentially resulting in legacy.
   b. Industrial and scientific applications of ionising radiation e.g. welding control, security screening, irradiators and particle accelerators.
   c. Military: former nuclear bomb testing sites, weapons fallout and nuclear-powered vessels (submarines, icebreakers and nuclear powered satellites).

III. **Human activities related to the use of natural resources, containing naturally occurring radionuclides (Naturally Occurring Radioactive Materials or Technically Enhanced NORM)**
   a. Mining, processing, waste management of natural resources containing natural radionuclides (NORM) (e.g. oil and gas extraction, NOR-rich ore mining).
   b. Use, processing, recycling and waste management of technologically enhanced naturally occurring radionuclides, including decommissioning of NORM affected industrial facilities.

IV. **Natural radiation as source of ionising radiation: telluric and cosmogenic radiation, natural events leading to radionuclide releases**
   a. High natural radiation background areas, potentially resulting in radon and thoron in indoor air and/ or in natural nuclides present in water/food.
   b. Exposure to cosmic radiation at high-altitude or in space.

2.2. Exposure scenario groups

Exposure scenarios cover a wide range of potential exposures of humans and the environment. These may originate from various anthropogenic or natural sources. Six exposure scenario groups related to the four contexts have currently been identified as shown in Table 1. The six scenario groups are presented according to the ICRP classification in planned, existing and emergency exposure situations. These scenario groups cover all the types of exposure situations potentially experienced by the public, patients, workers and the environment.

Each of the six scenario groups cover very large ranges of exposures of humans and the environment. However, the exposure scenario groups presented below provide sufficient information to deduce the joint research challenges of the joint roadmap. We have provided within the exposure scenarios, where available, indications of (collective) doses and general uncertainties or knowledge gaps to allow individual stakeholders to appreciate the relative importance of the scenarios from their perspective. The research challenges presented in Chapter 3 were developed according to these exposure scenarios, and must therefore be interpreted with the exposure scenarios in mind. More details on doses in specific exposure situations are available in UNSCEAR reports[2].

The relevance of exposure scenarios may differ in time and may vary strongly from different end users' points of view and values. A changing societal concern regarding protection of the environment may shed a different light on the relevance of some of the scenario groups. A new nuclear/radiological accident with radioactive environmental contamination may also impact on the societal concern related to radiation exposure. Global geopolitical changes could lead to uncertainties in responsibilities and emergency management. New reactor technologies or new sources such as floating reactors may induce different threats resulting in different accident scenarios. Climate change may alter environmental exposure, for example in legacy sites. Other external factors that may change the relevance of exposure scenario groups are an increased exposure of patients to medical radiation or an altered global health status, or exposure of humans and the environment to a combination of various stressors. Finally, progress in information technologies such as big data, artificial intelligence (A.I.), availability of human health data for (molecular) epidemiology and progress in emerging life sciences may positively influence the progress in radiation protection research.

[2] https://www.unscear.org/unscear/en/faq.html#Levels%20of%20radiation ,
https://www.unscear.org/docs/publications/2017/UNSCEAR_2017_Report.pdf
https://www.unscear.org/docs/publications/2016/UNSCEAR_2016_Report-CORR.pdf
https://www.unscear.org/docs/publications/2012/UNSCEAR_2012_Annex-A.pdf

Table 1. Exposure scenario groups related to different exposure situations categorised according to the ICRP classification (planned, existing or emergency exposure situations). The columns represent the different exposure sources (anthropogenic/natural) and contexts (medical, nuclear, NORM - TENORM and natural). Within the different exposure situations, various groups of exposure scenarios are identified. For emergency scenarios it should be noted that the first phase is classified as emergency while the recovery phase on the longer term is treated as legacy which is an existing exposure situation.

RP in various exposure scenarios		Anthropogenic	Anthropogenic	Anthropogenic	Natural
ICRP classification	**Contexts** ⇨ **Exposure Scenarios** ⇩	Medical therapy and diagnosis	Nuclear applications and applications of IR other than medical	Use of natural resources (NORM, TENORM)	Natural background radiation
Planned	1. Medical / Patients	Patients undergoing diagnostics or RT			
Planned	2. Industrial applications / public & environment		Discharges from nuclear sites during normal operation	Discharges from industry dealing with NORM	
Planned	3. Workers	Personnel in health care & production of radiopharmaceuticals	Personnel in nuclear installations & use of industrial IR sources	Personnel in NORM generating industries	Aviation personnel & astronauts
Existing	4. Nuclear or industry using NORM/ public & environment		Legacy from nuclear fuel cycle or other nuclear installations	NORM legacy sites	
Existing	5. Natural background / public & environment				Elevated natural background
Emergency	6. Nuclear or radiol. accident / public, workers, environment	Accident/incident with medical sources, radiopharmaceuticals	Accidents in nuclear installations	Accidental releases from NORM industry	

Scenario group 1 – Patient exposure from medical applications of X-rays, electrons or other particle radiation including the use of radiopharmaceuticals

This scenario group encompasses the medical exposure of patients to ionising radiation, for diagnosis and therapy. These exposures result in the highest average exposures to humans related to man-made sources of ionising radiation at least in developed countries e.g. in Europe, where the annual average dose of X-ray and nuclear medical imaging procedures is 1.1 mSv per caput still with a large variation between the different European countries, from which about 5% is due to nuclear medicine imaging procedures[3]. Dose ranges are very different amongst the various applications. However, there are body regions with low exposures in therapeutic applications while there are also body regions in e.g. interventional or cardiological investigations and repeated three-or four-dimensional imaging procedures with high local exposures. Thus, the scenario group will encompass all types of medical exposures.

The exposures to individual patients may vary substantially depending on their health status, the national health care system and the type of equipment technology used: For example, the average annual effective doses per caput from X-ray procedures in Europe range from 0.25 mSv in Moldova to 1.96 mSv in Belgium[4]. Each specific investigation might be performed within a large variety of parameters and settings within different countries, regions, hospitals or even departments. Many individual

[3] Study on European Population Doses from Medical Exposure (Dose Datamed 2, DDM2) Project report part 1: European Population Dose, page 9. Contract ENER/2010/NUCL/SI2.581237, 2010
[4] DDM2, table 5.13, part 1, 2010

members of the public may not receive any medical exposure in one year at all whilst some patients may undergo several abdominal CT scans each of which has an effective dose[5] of about 10 mSv.

A slightly increasing trend of average exposure per caput related to medical applications of ionising radiation is seen during the last few decades, and the awareness of adverse effects has pointed out the need for optimising imaging procedures in terms of a balance between an improved diagnostic outcome related to image quality and a reduced radiation exposure. Improving the quality of medical images usually means increasing the radiation dose to the patient, which in turn increases the radiation risks. For this reason, the objective of medical imaging is not to deliver the perfect image but one that is diagnostically adequate for the specific health problem[6]. Balancing image quality with radiation dose requires a special approach, since too low a radiation dose could be as bad as one too high: the images obtained could be of unsuitable diagnostic quality. Clinical auditing, reference levels and safety culture are among the means to improve optimisation. In addition, it is expected that technological innovations based on artificial intelligence will surpass the image detection capability of human eye after being trained by large datasets of image information. The distribution of exposures resulting from certain procedures like interventional or fluoroscopy-guided procedures can show differences in orders of magnitude resulting in local doses in the range of a few Gray. Exposure related to radiation therapy using external irradiation or radiopharmaceuticals may result in very high doses to tumours, of the order of multiple tens of Grays. Surrounding healthy tissues may also receive significant doses in the range of a few Gray, which may result in secondary effects such as acute inflammation, or late cancer / non-cancer diseases.

Especially, young children with higher radiosensitivity undergoing repeated examinations or radiotherapy may develop secondary effects. Like age, other individual sensitivities such as gender, disease-related effects, environmental risk factors like smoking or weight and genetic background are important to consider. Unravelling individual sensitivities may ultimately refine the system of radiation protection, especially in the context of medical applications.

Besides the development of direct radiation protection optimisation in terms of medical outcome per related risk through personalization and harmonisation of practices in diagnostic and therapeutic applications it would be feasible to study the secondary effects of medical exposures. However, it is important that assessment of secondary effects resulting from medical exposures takes into account the health status and drug intake of the patient.

Such research initiatives are only possible when regulations are adapted to support the harmonisation of medical practices and protocols, and to enable the use of relevant patient data for research, while respecting patient confidentiality.

The ultimate goal of research related to scenario 1 is to provide information to policy makers, national healthcare, health practitioners, patients and comforters of caregivers on optimisation strategies, to allow informed decision-making, and to adjust protocols to optimise (i) image quality and dose in diagnostics and (ii) target dose and healthy tissue dose in therapy.

[5] The meaning of effective dose in terms of medical exposures might be questionable; it should not be used for individual risk estimates. We refer to dose concepts in Challenge 2.
[6] https://www.iaea.org/topics/optimising-image-quality

Scenario group 2 – Exposure of the general public and the environment as a consequence of industrial applications of ionising radiation and the use of NORM in normal operation conditions

This scenario group covers a wide range of human activities. The operations linked with the nuclear fuel cycle (from uranium mining and milling up to final radioactive waste management, disposal and decommissioning), with industrial activities making use of ionising radiation as well as with the industries handling material containing natural radioactivity (NORM/TENORM), may lead to releases of radioactivity to the environment, which need to be controlled in order to minimise harm to individuals or to the environment.

To assess robustly the transfer and distribution of radionuclides in the environment from source to target (individuals and environment), fit-for-purpose models are required capable of capturing the required uncertainty. Uncertainties linked with exposure assessment may be related to the source characteristics, physicochemical behaviour and transport of radionuclides, transfer to biota, dosimetry and dose assessment in humans and biota.

In some cases, a full understanding of the bio-physico-geochemical processes affecting radionuclide mobility in biosphere, geosphere and atmosphere is required. This involves the development of models underpinned by dedicated laboratory and field experiments and studies and the development of dedicated data bases of parameter values. Special environments must acquire additional attention due to climate change. The representative person and reference area for biota should be adequately defined.

The human and environmental exposure and impact assessment, both for predictive (e.g. newly built) and operational situations, need to consider not only the radiological component but also societal and ethical aspects.

Potential (health) effects to individuals and the environment is expected to be negligible given the generally very low dose rate/annual exposure.

Scenario group 3 – Exposure of workers in normal operational conditions.

Next to patient exposure and exposure to natural radiation, exposure of workers in normal operational conditions results in the third highest effective dose to humans. The description of this scenario group is based on a summary of data from the ESOREX[7] platform, which was developed to gather information on occupational exposures in Europe. The information gathered by ESOREX included how personalised monitoring, reporting & recording of dosimetric results is structured in European countries. The ESOREX platform also collects reliable and directly comparable individual and collective exposure data in all occupational sectors in which classified workers are employed, i.e. in the medical field (e.g., diagnostic radiology, interventional radiology, radiotherapy, diagnostic/ therapeutic nuclear medicine, dental radiology, veterinary medicine), in nuclear industries (nuclear fuel cycle for civil and military purposes), in industries using radioactive sources (e.g. industrial radiography, X ray fluorescence, industrial gauges, electro-beam welding, radioisotopes production and conditioning, industrial irradiation, security screening), in NORM-related industries (e.g. ore mining & processing, handling and storage of NORM, oil & gas industries, coal combustion) and in activities where employees are exposed to natural background radiation (e.g. air crew).

The type of occupational exposure varies and could include exposure through inhalation (e.g., of radon or radioactive dust), external whole-body exposure (e.g. in various sectors and to air crew exposure to

[7]ESOREX platform: (1) Establishment of a European Platform for Occupational Radiation Exposure –Highlights of the final report Contract n° ENER/2012/NUCL/SI2.636456, Rapport PRP-HOM 2015-00010,2015; (2) website https://esorex-platform.org/

cosmic radiation), or external exposure of extremities and eyes to gamma radiation (e.g. in the medical sector), all of them potentially resulting in different health effects.

The mean value for monitored workers in 2015[8] for all categories was 0.27 mSv/year in European countries that provided data to ESOREX[9]. On the individual level, occupational exposures may be higher: From the data available for France in 2015, the annual average dose to measurably exposed workers[10] in NORM industry is the highest (i.e. 1.94 mSv) and originating mainly from Rn inhalation, followed by workers in industry using radiation sources (1.38 mSv), nuclear industry (1.17 mSv) and medicine (0.34 mSv), mostly as external exposures. To complete the list of occupational exposures, we include the annual average aircrew exposure in Germany in 2015 (which was not measured but calculated with suitable codes that include flight route and the field of secondary cosmic radiation in the atmosphere), which was 2 mSv, with individual aircrew exposures up to 6.5 mSv. Annual collective doses in France in 2015 in NORM industries, industries using radiation sources, nuclear industry and medicine were 38 770, 17 990, 27 450 and 15 380 manSv, received by about 20 000, 33 000, 70 000 and 200 000 workers, respectively.

Although protection against radon is primarily based on measurement and optimisation, dose estimates are required for workers if, despite optimisation, radon levels in a workplace remain above the national reference level (ICRP 126). The EU Basic Safety Standards Directive 2013/59/EURATOM widens the application of radiation protection practices to previously not affected fields such as exposures to radon, thoron (including their progeny) and exposures to NORM, and demands that they are regulated in the same way as artificial sources. Many open questions remain regarding dosimetry, effects and risks of radon and NORM when occurring alone or in combination with other stressors. Further knowledge is needed to significantly reduce scientific as well as technical uncertainties in all steps of the radiation risk management cycle for radon and NORM exposure situations. Effective doses arising from unit exposure to radon and its progeny have been calculated using either dosimetric models or using the so-called 'epidemiological approach'. Both approaches give consistent results within their associated uncertainties (ICRP 137). Taking account of both methods, ICRP has recently recommended a single reference dose coefficient to be used, in most circumstances, for workers in buildings and in underground mines. Reference values are also given for specific situations of indoor work involving substantial physical activity, and for workers in tourist caves (ICRP 137). In special cases, where exposure conditions are non-typical, where sufficient reliable aerosol data are available, and estimated doses are likely to be high, site-specific dose coefficients can be calculated using the dosimetric data provided in ICRP 137. This would require a careful analysis of the European workplaces with a coordinated action with an expert group performing field measurements for dose assessments.

A large number of workers are covered by all these scenarios mentioned above, and hence efforts are needed to improve the assessment of doses and to optimize radiation protection.

Awareness of and integration of protection culture into industrial planning and the implementation of the new BSS plays a key role for an optimized radiological protection.

[8]2015 is the most actual year for which most countries have provided results in the ESOREX platform

[9]ESOREX data including data from France, Germany, Greece, Switzerland, Finland, Slovenia, Spain, Lithuania, The Netherlands

[10]There is a difference between monitored and measurably exposed workers: compared to "*measurably exposed workers*", "*monitored workers*" include individuals not having received a dose above the recording level, which is mostly equal to the applied method's detection limit, or which have received doses equal or lower than the limits to the public (≤1 mSv).

Scenario group 4 – Exposure of the general public and the environment with regard to legacy.

Past development of commercial and military uses of radioactive material and material containing naturally occurring radioactive materials (NORM), led to the development of many nuclear or NORM facilities worldwide. In many countries, these facilities were built and operated before the regulatory infrastructure was in place to ensure proper emission and residue handling and end-of-life decommissioning. This has led to legacy sites worldwide, contaminated with long-lived radioactive and other toxic residues that may pose substantial environmental and health concerns. Other type of legacy is that linked with former nuclear bomb testing sites, areas where ammunition of depleted uranium was used, areas impacted by accidents of submarine or nuclear energy-driven satellites or orphan radiological sources. Legacy sites are characterised by a large variability, complex and heterogeneous features and cover a broad range of issues. These legacy sites may cause radiological (and chemical) exposure to man and wildlife and may entail health risks and/or induce ecological damage. To robustly assess exposure to man and the environment and propose remedial options fit-for-purpose, transfer and exposure models are essential. Justification and optimisation of the remediation strategy should involve a multi-criteria approach in which stakeholders are actively involved in each step.

Exposure of human beings and wildlife is generally higher at legacy sites than at nuclear and NORM sites under normal operation. Impact assessment for individuals and environment is hence generally more crucial than for scenario 2. Since public exposure is sometimes in a dose range where there are uncertainties in the effects, scientific development is essential to predict health effects at these 'low' dose rates and related total dose.

Proper site characterization, human and environmental exposure and impact assessments, safety assessments and evaluation of remediation options (in terms of technical performance, associated exposure reduction and social impact), constitute the basis for decision making and need to be based on robust scientific and technological developments, as well as on the concerns of the various stakeholders. They ought to integrate uncertainty estimates that would help identify the priorities for scientific research to be dedicated to the most uncertain processes/parts of the assessment and take into account at the same time societal uncertainties and ethical implications of decision-making.

Scenario group 5 - Exposure of the public and the environment to the natural radiation environment

Radiation emitted from natural terrestrial sources is in most European countries responsible for about half of the average annual dose to humans. It is largely due to primordial radionuclides, mainly 232Th and 238U series, and their decay products, as well as 40K, which exist at trace levels in the earth's crust. Their concentrations in soil, sands and rocks depend on the local geology of each region in the world. The average natural radiation exposure is 2.4 mSv/y (global average)[11], but may vary strongly from place to place (from < 1 mSv/year to 100 mSv/y). Indoor radon is the largest contributor to the natural radiation exposure of the general population and the link between radon exposure and development of lung cancer is well established. Notwithstanding the recent recommendations of ICRP, there is a need to improve the knowledge of factors modifying the relationship between radon exposure and effects, as for example the interaction of radon with smoking habits or the radon-related risk for diseases other than lung cancer.

In recent years, several international studies have been carried out on the effects of background radiation on human health, but they are not fully conclusive on the specific radiation effect given the low dose rate, the impact of confounding factors etc. A more comprehensive dedicated international

[11] UNSCEAR 2008 Annex B Table 12; it must be noted that different countries apply different dose conversion factors. Therefore the average dose should be regarded as a representation of the order of magnitude of the dose.

study is required. Another uncertainty concerns the possible relationship between background irradiation and cancer incidence, particularly in children.

High background areas might be regarded as ecosystems exposed to long-term low-dose radiation. Comparison of such ecosystems with other ecosystems in areas with much lower background radiation levels might reveal important evolutionary information on various populations.

Information on scenario 5 is important to inform public and legislators about the effects of natural radiation, and to assess the eventual needs for countermeasures to be taken to reduce the exposure of the general public and/or the environment.

Scenario group 6 – Exposure of the general public, workers and the environment following a major nuclear or radiological accident or incident including long term consequences

This scenario includes all types of incidents or accidents in nuclear installations, medical facilities, transport of nuclear material, military installations and operations (e.g. 'broken arrow' incidents such as the incident at Palomares, Spain), lost sources (such as the Goiânia accident in 1987), satellite return (such as the SNAP-A re-entry event) or other events involving uncontrolled exposure or spread of radioactivity.

The impact on the affected population might range from local (e.g. a lost source) to worldwide (e.g. Fukushima and Chernobyl) and is not limited to individual health effects but may affect the environment as well as economic and social activities, e.g. all possible living conditions and lifestyle of affected people. This scenario also covers accidents related to the medical use of ionising radiation. This includes among others accidental and unintended medical exposures, overexposure and incorrect treatments of patients.

The timescales may range from days to decades or even longer, thus appropriate means must be developed to deal with the related challenges as defined in Chapter 3. Preparedness, supporting scientific tools and engagement of all relevant stakeholders are some of the necessary scientific input to deal with the consequences and mitigate them as much as possible.

3. Deriving joint research challenges and game changers from radiation protection contexts and exposure scenarios

"Joint research challenges" were developed, based on the scenario groups (section 2.2), taking into account the priorities identified in the strategic research agendas and individual roadmaps and interactions with CONCERT POMs and stakeholders. An overview of the joint research challenges is presented in Table 2. The term "joint" refers to the fact that the joint research challenges cover many disciplines, requiring collaboration of research communities of the different radiation protection research platforms. Table 2 summarises in the last column the different platforms needed to tackle the challenges. Most of the joint research challenges are relevant within various exposure scenario groups. For example, a better understanding of the human health effects at realistic low doses or dose rates is relevant in all exposure scenarios, even though the specific dose ranges or dose rate ranges and radiation qualities may differ according to the exposure situation.

Table 2 Overview of joint research challenges derived from the exposure scenario groups, addressing research disciplines available in the various radiation protection research platforms. The main platforms involved in the different research challenges are explicitly presented in the last column.

Joint Research Challenges	Scenarios	Platforms involved
A. Understanding and quantifying the health effects of radiation exposure	1-6	MELODI + All
B. Improving the concepts of dose quantities	1-6	EURADOS + All
C. Understanding radiation-related effects on non-human biota and ecosystems	1-2, 4-6	ALLIANCE, NERIS, EURADOS, MELODI, SHARE
D. Optimising medical use of radiation	1, 3	EURAMED, EURADOS, MELODI, SHARE
E. Improving radiation protection of workers	3, 6	EURADOS, MELODI, EURAMED, NERIS, SHARE
F. Integrated approach to environmental exposure and risk assessment from ionising radiation	2, 4-6	ALLIANCE, NERIS, MELODI, EURADOS, SHARE
G. Optimise emergency and recovery preparedness and response	6	NERIS + All
H. Radiation protection in society	1-6	SHARE + All

Within the joint research challenges, various "game changers" have been defined as *"Research that, when successfully executed, has the potential to substantially impact and strengthen the system and/or practice of radiation protection for man and/or the environment through 1) significantly improving the evidence base, 2) developing principles and recommendations, 3) developing standards based on the recommendations and 4) improving practice"*. As such, the authors estimate that funding research as defined in the game changers will maximise the potential to address the joint research challenges derived from currently realistic exposure scenarios.

It is important to notice that the proposed challenges and game changers are a current snapshot, sensitive to the evolution of the state of the art, or to future alteration of exposure scenarios, and accomplishment depends strongly on the resources available, as discussed in Chapter 5. Whereas the joint research challenges have already been presented to and validated by stakeholders in 2018-2019, the game changers are new and will be presented for priority setting to researchers, stakeholders and end users. To include this information, the joint roadmap will be updated in May 2020 as the last version within the course of EJP-CONCERT. The level of detail provided in the research challenges and game changers is very restricted. More detail is available for specific topics in the SRAs of the different radiation protection research platforms in Annex 2.

3.1. Challenge A – Understanding and quantifying the health effects of radiation exposure

The central aim of radiological protection is the protection of human health from the harmful effects of ionising radiation. Risks to health are the prime consideration in all situations of radiation exposure that include humans and are therefore of relevance to radiological protection in all occupational, medical and public exposure situations, under normal or emergency conditions. The ultimate goal of this challenge therefore is to have a comprehensive quantitative and mechanistic understanding of all radiogenic health effects.

Figure *3* summarises the current understanding of the relationship between radiation exposures and health effects (UNEP, 2016)[12]. In the context of the Joint Roadmap, low doses and/or low dose rates refer to a range of acute and/or protracted exposures of ionizing radiation that are typical of those encountered in the workplace, the environment and in diagnostic medicine. Moderate doses refer to doses that may be encountered by normal tissues in interventional radiography or in radiotherapy or in nuclear or radiological accidents. Doses below 100 mSv in a year may be considered low, and doses of the order of 100 – 1000 mGy are considered moderate. Doses higher than 1000 mSv are considered high and may cause symptoms of acute radiation sickness if received during a short period. Low dose rate means relatively low rate of dose accumulation. In radiological protection context, annual dose rates below 100 mSv may be considered low.

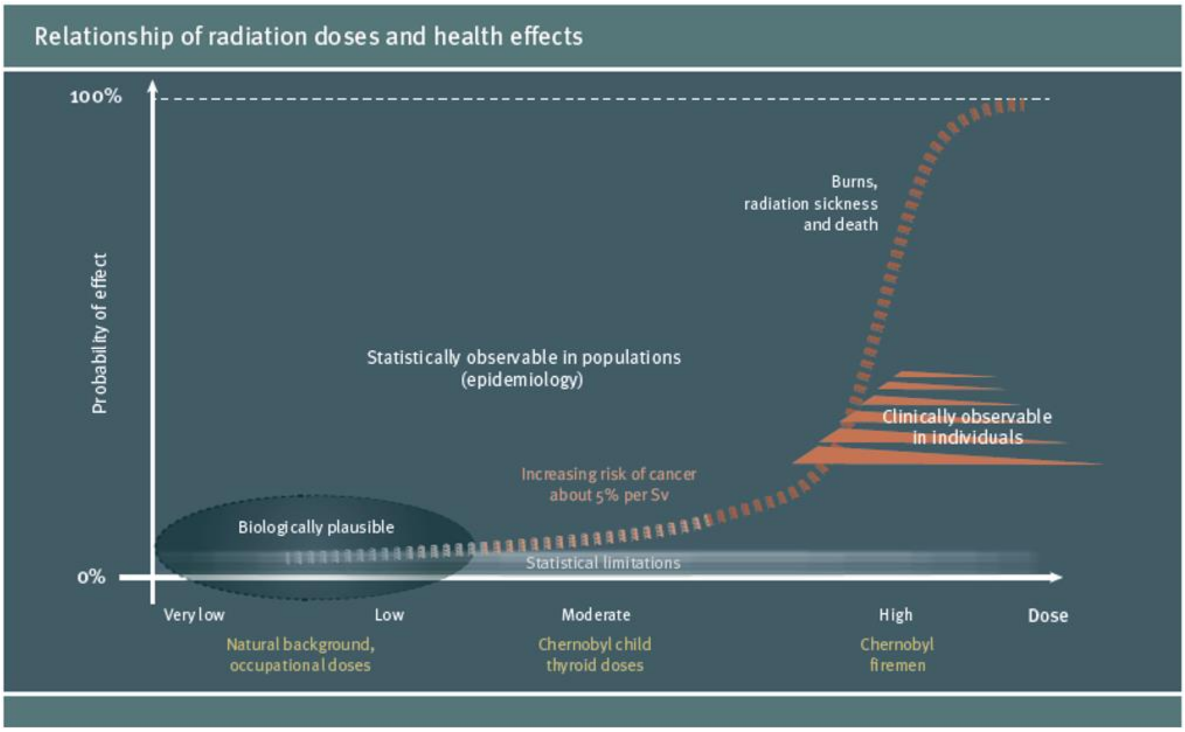


Figure 3. Relationship of radiation doses and health effects (UNEP, 2016). Dose ranges are defined in the text.

[12]RADIATION – Effects and Sources, United Nations Environment Programme, 2016, ISBN: 978-92-807-3517-8

It is important to distinguish between observations of early health effects in exposed populations from theoretical projections of potential future effects. For both situations, it is important to consider any uncertainties including those related to radiation measurements, statistical considerations or other factors. Currently, health effects can be reliably attributed to radiation exposure if early effects (e.g. skin burns) occur in individuals, e.g. after doses greater than 1 Gy (for teratogenic and other developmental effects possibly greater than 100 mGy). Using epidemiological methods, it is possible to attribute an increased occurrence of delayed health effects (e.g. cancers) in a population exposed to moderate radiation doses. However, there are no validated tumor biomarkers presently available to distinguish whether a cancer has been caused by radiation exposure or not. Where the level of radiation exposure was low or very low, changes in the occurrence of delayed health effects may be observed in epidemiological investigations; however, there are statistical and other uncertainties and a lack of full mechanistic understanding of the pathogenesis related to ionising radiation or other stressors. Unequivocal determination that cancers occurring after low dose exposures are caused by the radiation exposure is rarely possible. The LNT (Linear Non Threshold) approach suggests that epidemiological data from the higher dose range can be extrapolated to lower doses in a linear way. Understanding the mechanisms of radiation action helps in judging the biological plausibility of cancer induction by radiation exposure. Such mechanisms include the recognised DNA damage/gene mutational pathways and others such as potential epigenetic mechanisms, and disruption of mitochondrial function leading to persistent elevation of reactive oxygen species, amongst others.

Exposure limits in radiation protection are based on knowledge of radiation cancer risk derived from epidemiological studies and assumed risk of heritable effects in humans. Epidemiologically derived health risk estimates are limited in power below around 100 mSv; depending on the cancer type, the applied models for risk inference can be linear or linear quadratic. However, for risk management purposes, it is a linear non-threshold (LNT) model that is applied, justified on the basis of a biologically plausible argument that relates direct damage to nuclear DNA to mutations in specific genes that drive carcinogenesis. The mutational action of radiation may be modulated by other processes, some not well characterised throughout the prolonged periods over which cancers develop. In addition to cancer risks, there is increasing evidence of risk of non-cancer conditions, notably circulatory disease, cataracts and cognitive effects at lower doses, more than previously recognised.

Refinement of risk assessment for both cancers and non-cancer diseases can be improved by further large-scale epidemiological studies with good exposure assessment/dosimetry and integration of mechanistic biological understanding of radiation-induced disease processes. There is a need to further characterise organ-specific sensitivity and the distribution of risk within the population (evidence points to age, gender, co-morbidities, genetic factors, exposure to other environmental risk factors and life-style/behavioural factors as risk modifying factors). Information on the effects and risks associated with internal exposures, exposures to mixed radiation fields, co-exposures to radiation and chemical agents, differing radiation qualities, and inhomogeneous exposures is needed.

The major issues ('game-changers') to resolve with potential impact to the radiation protection system and or practice in this area are:

Game Changers	Potential impact on the radiation protection system and/or practice
A1. Define the risks of non-cancer diseases at low and intermediate dose levels (100 - 500 mGy and below). Priority with highest potential to advance understanding in the short term (5Y): circulatory effects at near-field / out-of-field therapeutic doses and dose-rates and following interventional radiology; Long-term research topics: cerebrovascular / neurocognitive, metabolic and immune diseases, at progressively lower doses	If present, these risks could lead to re-consideration of calculations of radiation detriment, dose limits and reference levels; there would also be a need to re-consider tissue weighting factors and potentially additional protection measures.
A2. Integration of epidemiological estimates of cancer risk with a more complete understanding of radiological disease pathogenesis to improve cancer risk assessment Priority with highest potential to advance understanding in the short term: defining processes contributing to cancer development after exposure; e.g. role of epigenetics, metabolic status, in single and multiple stressor at low doses and dose-rates Long term research topics: definition of target cell populations and cell interactions/microenvironmental effects	If a dose and dose-rate effectiveness factor is no longer needed, or requires alteration, this could lead to reconsideration of dose limits. Should a signature that unambiguously identifies radiation-induced cancers be identified, this would have impacts for compensation scheme criteria and programmes. Developing an understanding of all contributory mechanisms for radiation carcinogenesis at low dose/low dose rate, and the associated dose-response relationships, is essential for the development of risk projection models and predictive biologically based models Knowledge of the nature and size of target cell populations for radiation carcinogenesis is critical for further development of biologically based predictive modelling
A3. For deterministic and stochastic cancer and non-cancer outcomes: **Characterisation and quantification of variation in response and risk between population sub-groups/individuals due to genetic factors, sex, co-morbidities, dedicated exposure of disease areas in patients, environmental and lifestyle factors and the interactions between these depending on dose levels.** Priority with highest potential to make progress in understanding in the short term: Evaluation of potential predictive factors and correlating them with health outcomes. To improve the understanding in the difference of the dose response curve shape between males and females, as observed in the LSS cohort Longer term research topics: Integrative radiobiologically oriented systems biology, setup of	If a robust (specific, sensitive) predictive metabolic status and biomarkers or radiomic markers for radiosensitivity (tissue reactions) were found, this would allow more individualised cancer treatment. Knowledge on the range of variation in susceptibility to stochastic effects in populations would be informative for public health and development of the system of radiation protection. A better understanding of the mechanisms involved in long term effects of ionising radiation may be integrated with mechanisms resulting from exposure to other stressors or from combined exposures. On the longer term, an integrative protective system could be established to cover realistic multi-exposure scenarios. A confirmation of the difference between sexes in the shape of the dose response (males: linear-quadratic and females: linear) may lead to changes in levels of exposure limits.

adverse outcome pathways related to ionising radiation and in combination with other stressors including diseases. Seeking biomarkers of individual risk through cellular/molecular and systems biological approaches as well as radiomics investigations	Moreover, a better understanding and validation of the impact of life-style factors on the risk of stochastic and tissue effects could contribute the reduced risk by modifying life style. The dedicated response of diseased organs are of primary interest in taking care of patients since in diagnostic as well as therapeutic procedures mainly diseased organs will be exposed.
A4. For stochastic cancer and non-cancer outcomes: **Define how the temporal and spatial variations in dose delivery affect the risk of health effects following radiation exposure.** <u>Priority with the highest potential to make progress in understanding in the short term:</u> Addressing the difference between risks from acute and chronic exposures through the integration of experimental and epidemiological data applying biologically-based risk models To improve the understanding of the effects of intra-organ dose distribution through observations in patients exposed to inhomogeneous dose distributions and experiments with organotypic tissue models. <u>Longer-term research topics:</u> Addressing the difference between risks from internal and external exposures through the integration of new knowledge on the effects of chronic exposures, intra-organ dose distribution and radiation quality considering energy deposition at different scales (from intra cellular to organs).	A strengthened evidence base may impact on judgements on dose rate effectiveness factors and radiation weighting factors (potentially including those for non-cancer outcomes) as well as in the introduction of new weighting factors accounting for the effects of modulation of intra-organ dose distribution. Changes in these factors would lead to reconsideration of dose limits, reference levels, conversion coefficients and dose coefficients for intakes of radionuclides.

3.2. Challenge B – Improving the concepts of dose quantities

The dependence of biological effectiveness on radiation quality is commonly believed to be related to the differences in the energy deposition pattern on a microscopic scale. For charged particles, this pattern is called the particle track structure, where for heavy particles, such as ions, the energy transfer points are concentrated around the primary particle trajectory. Identification and quantification of the relevant statistical characteristics of the microscopic spatial pattern of interactions (e.g., spatially correlated occurrence of clusters of energy transfer points) are an essential prerequisite for improvement of present dose concepts. Micro- and nanodosimetry have provided experimental and computational techniques for the microscopic characterization of the track structure.

The overarching objective is the development of a novel, unified concept of radiation quality as a general physical characteristic of the radiation field that would allow separating the physical and biological components contributing to the eventual biological effects of radiation.

The comprehensive multi-scale characterization of the physical aspects of particle energy deposition will enable a quantitative investigation of the impact of track structure in terms of biological effects. Track structure has been proven to show a strong correlation with the induction of early biological effects, particularly the occurrence of DNA single and double strand breaks. As later biological endpoints also show dependence on radiation quality, there should also be a correlation of track structure characteristics and the probability of inducing these later effects, such as chromosomal aberrations or cell death. The ability to establish these correlations at the cellular level and investigate the response at supra-cellular organization level will form the basis for the comprehension of the radiation damage mechanism.

The major issues ('game-changers') to resolve with potential impact to the radiation protection system and or practice in this area are:

Game Changers	Potential impact on the radiation protection system and/or practice
B1. To improve the understanding of spatial correlations of radiation interaction events by improved measurement and simulation techniques.	Understanding the physical interaction between radiation and matter is a start for finding the low dose effects for different kind of particles
B2. To quantify correlations between track structure and radiation damage	This fundamental knowledge will have a direct impact in addressing current optimization criteria in diagnostics and radiation therapy and radioprotection, such as "biologically weighted" doses delivered in hadron therapy, dose calculation in inhomogeneous irradiations such as those of short-range α- and β- emitters used in nuclear medicine or in the case of internal contamination, risk estimation for low dose exposures, etc…

3.3. Challenge C – Understanding radiation-related effects on non-human biota and ecosystems

The need for an explicit demonstration of the protection of the environment (or wildlife) from radioactive releases was recognised during the last decade (ICRP, 2007; EC BSS, 2013; IAEA, 2014). Also, human health is in the long-term directly related to the fitness of the ecosystem. Environmental exposures at low dose and dose rate are relevant for many planned exposures situations under normal operation conditions (scenarios 2), existing environmental exposure scenarios with regard to legacy (scenario 4) and natural radiation (scenario 5), as well as long-term exposures after accidents (scenario 6).

The current knowledge about the radiation effects on wildlife was used in the last decade to develop appropriate radiological environmental impact assessment tools and to derive the associated protection benchmarks. For example, dose rates for reference animal or plants within which there is likely to be some chance of the occurrence of deleterious effects (DCRLs, derived consideration reference levels) were suggested from 0.1-1 to 10-100 mGy day-1, accounting for the variation in sensitivity of the considered wildlife group (ICRP, 2008). However, most of the available knowledge used to derive such benchmarks is related to the risk to individual organisms, whereas populations, ecological function and structure, and the preservation of biodiversity are more relevant from a management perspective and should be the focus of future studies.

On the other hand, there is considerable scientific disagreement on the actual extent of the radiation effects on wildlife populations in contaminated areas. Many studies have reported no significant effects of radiation on wildlife (e.g. in the Chernobyl and Fukushima exclusion zones), whereas others reported significant radiation effects on different wildlife populations at very low dose rates (below natural background exposure). This questions the robustness, the representativeness and the scientific consensus of actual diagnostic tools with regard to the long-term consequences of radiation exposure on non-human biota and ecosystems. This controversy has major implications for the robustness and the credibility of the system of radiation protection and resolving it would be a major game changer.

The robustness of radiological environmental impact assessment can be improved both by the understanding of underlying mechanisms that governs the sensitivity of wildlife populations to radiation (link with Challenge A for radiation effects on humans), and by an actual understanding of ionising radiation effects on key ecosystem processes under realistic conditions, associated with a robust exposure assessment (including internal exposure, heterogeneity, differing radiation qualities – link with Challenge B) and considering other stress factors.

To achieve this, the major issues are:

- To identify the key factors determining the vast variation in the sensitivity of wildlife populations to radiation.
- To characterise the influence of exposures on the populations currently living in contaminated environments (whole exposure assessment, including past exposures).
- To identify and validate biomarkers of exposure and effects that are relevant for effects at the population level.
- To understand the impact of multiple stressors - contaminants and other environmental factors - on the effects of radiation.
- To determine the effects of radiation on ecosystem functioning.

The major issues ('game-changers') to resolve with potential impact on the radiation protection system and or practice in this area are:

Game Changers	Potential impact to the radiation protection system and/or practice
C1. Resolving the controversy with regard to the effects on wildlife reported in the Chernobyl and Fukushima exclusion zones Short term priority activity. This requires to: - characterise the influence of exposures on the populations currently living in contaminated environments (whole exposure assessment, including past exposures), - identify the key factors determining the vast variation in wildlife populations' sensitivity to radiation, - - identify and validate biomarkers of exposure and effects that are relevant for effects at the population's level.	The re-interpretation and achievement of robust, consensus-based data on the long-term ecological effects attributable to radiation in those emblematic contaminated territories would have a very significant impact on the confidence and credibility level of the radiation protection of the environment (e.g., robustness of 'no-effect' benchmark dose-rates).
C2. Determine the effects of radiation on ecosystem functioning Longer term priority activity.	If an increased sensitivity of ecosystem processes (in comparison with the reported effects at the population level) is demonstrated, this would strongly question the robustness of risk assessments that rely only on population-effect data. On the other hand, if it is shown that the functional or structural redundancy of the ecosystems brings greater robustness against the effects of radiation, the conservatism of the current assessments would be comforted.

3.4. Challenge D – Optimising medical use of radiation

Medical use of ionising radiation is the largest source of exposure on average for the population in developed countries as in Europe. However, there is a large difference in radiation exposure due to medical applications between different European countries and there is also a difference in the medical use itself. Therefore it is of great importance for the system of radiological protection to optimise the medical application of ionising radiation and to harmonise the practices throughout Europe especially with respect to the protection of human health from the harmful effects of ionising radiation and with respect to the potential benefit of the use of ionising radiation for the individual patient. The ultimate goal of this challenge therefore is to optimise the use of ionising radiation for the diagnosis and treatment for each patient on an individualized approach in a standardized way throughout Europe. The corresponding research needs to include the basic investigations as well as the transfer into clinical routine.

The European Commission summarised the different use of ionising radiation between different European countries in terms of the average radiation exposure caused by medical applications[13]. The existing technologies are not used or available in the same way for all patients throughout Europe. This means that patients in some countries will benefit more from the use of ionising radiation than those in other countries, but also that there is potentially more detriment due to the more intensive use of ionising radiation. In addition, there are many new emerging technologies in various fields of medical applications such as targeted therapies based on ion or proton therapy or targeted radionuclide therapy, new technologies for interventional imaging procedures and molecular imaging approaches. Optimisation of existing methods can nowadays be achieved by hardware developments as well as by data processing tools. One aspect of these data processing methodologies will be the use of artificial intelligence for optimised usage of the existing data. Thus, it is obvious that sufficient data structures for research and clinical use is a prerequisite for the optimisation of the medical use of ionising radiation and the corresponding optimisation of radiation protection. For all new and emerging technologies and technological approaches it is necessary to:

- Develop potentially optimising methods and technologies depending on requirements and needs of medical specialities.
- Optimise and develop accurate individualised patient dosimetry for all organs (and even at sub-organ level)
- Optimise the protocols for performing the diagnostic or therapeutic task related to the individual patient.
- Characterise such methods in terms of related exposure, but also image quality or physical therapy quality
- Evaluate and describe their potential benefit and risk taking into account individualized patient parameters
- Transfer such optimised approaches into the clinics
- Harmonise its use throughout Europe based on evidence.
- Foster an improved radiation benefit-risk dialogue with patients and the pubic

This shows that the main focus of challenge D has to be to allow the harmonised use of the most modern and beneficial use of ionising radiation throughout Europe, taking into account individual patient conditions to guarantee the best possible radiation protection of patients throughout Europe. To establish a suitable way of harmonisation it will be necessary to rely on various methods for characterisation of the technologies which will partly interact with other challenges. The characterisation of exposure is essential especially for the patients but also for the staff involved with a practical diagnostic or therapeutic procedure. This has to take into consideration the individual sensitivity or susceptibility of the patient. Finally, there has to be a characterisation of the potential benefit i.e. the potential accuracy of the diagnostic procedure or the accuracy and related potential beneficial outcome of a therapeutic approach. Thus, the characterisation of the procedure is not only necessary in terms of exposure but also regarding image quality or therapeutic quality measures.

The major issues ('game-changers') to resolve with potential impact to the radiation protection system and or practice in this area are:

[13] RP 180 Medical Radiation Exposure of the European Population, Part 1 https://ec.europa.eu/energy/sites/ener/files/documents/RP180.pdf and Part 2 https://ec.europa.eu/energy/sites/ener/files/documents/RP180%20part2.pdf

Game Changers	Potential impact to the radiation protection system and/or practice
D1. Development of new medical applications or optimisation of existing ones depending on disease related applications e.g. interventional procedures, CT based approaches, targeted therapies in nuclear medicine and particle based therapies to improve patient protection relying on corresponding improved dosimetry procedures for individual patients. <u>Priority with highest potential to advance optimised use and corresponding radiation protection (5Y):</u> new interventional procedures, CT based approaches, targeted therapies in nuclear medicine and particle based therapies <u>Long-term research topics:</u> molecular imaging, theranostics	New methodologies or optimised approaches can reduce the radiation exposure to each patient while maintaining or even improving clinical outcome and help to allow similar conditions for patients within Europe and require new or even potentially additional protection measures. The development and characterisation of such technologies will need to rely on improved dosimetric methods especially those suitable for personalized patient dosimetry and quality metrices predicting clinical outcome.
D2. Application and development of AI methods to improve patient protection relying on suitable clinical data structures and taking into account the limits of the use of AI especially in the medical field. To make use of the potential of methods based on artificial intelligence to optimise and better characterise imaging and therapy techniques and to analyse patient data. <u>Priority with highest potential to make progress in applications of AI in medicine in the short term:</u> development of suitable data structures to be able to use the generated patient data for AI methodologies, to understand the limits of the use of AI especially in the medical field and develop corresponding test configurations <u>Longer term research topics:</u> Ethics when applying AI based methods for decision (support) systems especially regarding radiation based therapies, AI based optimisation of individualised procedures	AI will play a major role in optimising and individualising medical applications in all fields. However, it is of major importance, that there is a profound understanding of the limits of such approaches in terms of reliability of results but also in terms of ethical implications. AI will allow further optimisation and individualisation of procedures and thus influence the corresponding radiation protection system dramatically, but in the field of medical ionising radiation it has to be controlled very well, otherwise misleading results might result in detrimental non-helpful exposures. The European radiation protection system has to define standards allowing best potential use of AI and thus improve the system for patients and industry.
D3. To transfer the (optimised) technologies and procedures into clinical / medical practice and harmonise it throughout Europe **Investigating key challenges and problems for the transfer of developments into clinical practice, evaluating conditions leading to large differences throughout Europe, defining standards for justification of applications depending on individual patient characteristics and benefit-risk evaluations of procedures including a dedicated education guaranteeing the best possible radiation protection for patients** is of great importance**.**	A strengthened evidence base medicine, a better justification as well as a concept for education and training together with a clinical transfer concept will allow harmonised practises in Europe based on the optimised and individualised medical procedures using ionising radiation. Therefore the radiation protection system for medicine would be harmonised and allowing better patient care with harmonised exposures throughout Europe.

Priority with the highest potential to improve the radiation protection system in Europe in the short term: Investigating key challenges and problems for the transfer of developments into clinical practice, evaluating conditions leading to large differences throughout Europe, defining standards for justification of applications depending on individual patient characteristics and benefit-risk evaluations of procedures and including a dedicated education and training programme Longer term research topics: Evaluation of newly developed or optimised procedures regarding benefit-risk outcome (evidence based medicine) Development of a framework for clinical transfer and harmonisation.	

3.5. Challenge E – Improving radiation protection of workers

Exposure to ionising radiation continues to be an important concern in many industries and applications in Europe (e.g. nuclear, medical, air travel), including various and often complex exposure scenarios. Consequently, radiation protection of workers is a major issue that requires continued improvement.

Internal exposure assessment of occupational exposure from incorporated radionuclides is still subject to major uncertainties, mainly due to activity measurement errors, individual variability and limited biokinetic and dosimetric models. The resulting overall uncertainty in the estimated internal dose is acknowledged to be generally higher than that for external irradiation. In vivo measurements, for example, can provide information on the actual radionuclide activity within the body of an individual. However, there is no standard procedure for calibrating the required detection systems (body counters), and the anthropomorphic phantoms needed, such as those used to assess the skeletal activity of bone seeking radionuclides (e.g. plutonium and americium isotopes) are scarce.

Furthermore, biokinetic models for various radionuclides and individual parameters (which may also include changed body metabolism of patients and effects of decorporation therapies) are still limited, and their predictions would benefit from the use of available databases including human autopsy cases.

For external exposures, monitoring of individual workers will benefit from real-time monitoring of all limiting quantities (e.g. whole body, eye lens, extremities, brain, heart) including well characterized active and passive dosimeters, or computational approaches using Monte Carlo (MC) techniques.

In this context, neutron dosimetry raises particular problems. Some neutron applications in industry represent well-known but as yet unsolved problems such as the inevitable existence of photons which might interfere with the detection of neutrons. Others imply newly evolving problems due to strongly pulsed radiation or very high neutron energy ranges, i.e. radiation fields around high-energy particle accelerators and during flights at high altitudes or in space missions. For external exposures, the challenge is to assess relevant dose quantities in real-time. This should include all radiation qualities and in particular photons and neutrons, static and pulsed fields, and a vast range of radiation energies up to GeV. Appropriate neutron reference fields will need to be developed. These efforts, together with improvements in procedures for dose optimization and improved protection measures, will significantly contribute to a safer use of ionising radiation.

Leaving the Earth's surface to space, humans have to cope with numerous stressors, such as environmental changes, disrupted circadian rhythms, isolation, microgravity and heightened levels of radiation. Exposure to ionizing radiation has been one of the major concerns since the beginning of human spaceflight and represents a critical obstacle to further progress for long-term space missions, because individual doses are usually much higher than on Earth. Radiation in space is a complex mixture of all particles and energies. The particle energies range from a few eV up to 1020 eV. They are incident isotropically and are very penetrating in matter, hard to shield and of high biological effectiveness. The radiation field in space is not constant as the energy and fluence spectra are modulated by the solar cycle by a factor of two to three with sudden increases due to solar particle events (SPEs) mostly occurring during periods of increasing and decreasing solar activity. Moreover, the field is modified by planetary atmospheres and surfaces, planetary magnetic fields, spacecraft construction materials and lastly by the interaction with the molecules of the human body. Production of secondary particles in nucleus-nucleus interactions prevents adequate shielding against galactic cosmic radiation (GCR). The challenge is to provide accurate information (energy and particle spectra, dose rates, and microdosimetric quantities) in each exposure situation.

Radon is the most important natural source of ionising radiation with the most important health effect being lung cancer. In some cases, this is of relevance for workplaces (mines, water works, spas, caves). Environmental monitoring for radon and other radiation hazards needs to be improved according to the recently published ICRP Publication 137 on Occupational Intakes of Radionuclides. In addition, radon tracer methods should be included in environmental climate networks such as the Integrated Carbon Observation System (ICOS).

Finally, a key aspect across all applications and domains involving workers' exposures to ionising radiation is the development of radiation protection cultures in support of improved decision-making processes regarding the management of exposure situations and the involvement of the relevant stakeholders in the identification and implementation of radiological protection actions.

The major issues ('game-changers') to resolve with potential impact on the radiation protection system and or practice in this area are:

Game Changers	Potential impact on the radiation protection system and/or practice
E1. Development of biokinetic models and personalised dosimetry that will lead to the improvement of the assessment of internal exposure	Reduction of the uncertainty of internal dosimetry towards the level of external dosimetry
E2. Development of real time practical individual dosimetry of workers by harnessing the developments in new connected technologies	Real-time practical individual dosimetry of workers for all organs
E3. Development of a practical neutron personal dosemeter	Reduction of the uncertainty of neutron dosimetry towards the level of gamma dosimetry

3.6. Challenge F – An integrated approach to environmental exposure and risk assessment from ionising radiation

Faced with environmental exposure situations (all scenarios except scenario 1 and 3) where various environmental and human-population related factors strongly interact, holistic approaches to risk assessment are increasingly justified to ensure sustainable and safe use of radioactive substances and to protect both human and ecosystem health. Concurrently, integration of scientific, societal and economic considerations is needed, if more integrated dose and risk assessment approaches are to be developed to meet societal expectations, better inform decision-making and improve risk communication among stakeholders.

As a basis for more robust exposure assessment we need to further **improve the understanding and associated modelling of radionuclide dispersion and transfer processes** in the geosphere and biosphere. This needs to include the dispersion and transfer assessment in marine, brackish, estuarine, freshwater and terrestrial ecosystems (agricultural, forestry, natural and urban), covering the watershed continuum from the source to the ocean and ultimately at the global circulation level. The goal is to produce advanced environmental modelling to improve human and environmental dose assessment. This goal will most efficiently be reached by collaborating with wider environmental sciences. Models should be improved, or developed, to allow for the interaction at the various biosphere interfaces at the local, regional and global scales.

Specific emphasis is required on **integrated and holistic assessments**. There is a need for the improvement/development of innovative methods to characterise the source terms to delineate the multiple-hazard footprint (e.g., geostatistical interpretation of environmental, radiological, chemical data) of a site in space and time. Innovative modelling approaches are also needed to support decision making and to identify the most significant sources of uncertainty related to the impact on human and environmental health.

Such scientific advances would help in the development of improved international guidance on the management of legacy sites (e.g. from past NORM activities or accidental exposures); such sites may represent relatively higher exposure scenarios. Such sites often represent complex “objects” to be managed via a multistage process including site characterization, definition of objectives for remediation, impact and risk assessment, and evaluation and selection of remedial options. Each step comprises an associated uncertainty analysis, which is of both technical and social in nature.

The major issues (‘game-changers’) to resolve with potential impact to the radiation protection system and or practice in this area are:

Game Changer	Potential impact to the radiation protection system and/or practice
F1. Deriving a robust prediction of radiological contamination in the human food chain, for an integrated dose and risk assessment of post-emergency situations	If successful, the resultant models (largely improved/developed based on a thorough assessment of available data and models) will be applicable in any relevant environment, to its time-evolution, to any human/animal food. They will especially include future changes in European agricultural practices, and, since NPPs are often build on the coast, and since in the future more NPPs built on floating vessels are expected, we need further developments in marine dispersion and biota transfer models.

	Models developed will be transferable, meaning that they will already include the necessary amount of processes that allows model applicability to different scenarios. This will result in optimized management in the emergency and post emergency phase with respect to dose assessment, food chain protection and control, remedial actions, economic and societal impact.
F2. Identifying and quantifying the key processes that influence radionuclide behaviour in existing environmental contamination situations	Implementation of the new Basic Safety Standards (BSS), applying to the management and clean-up of existing sites, as well as to the licensing of future discharges and large quantities of NORM waste, developing the modelling basis for accurate dose assessment and establishment of remediation approaches is of important added value to society. This is especially important as NORM legacy or operationally impacted sites are often close to human habitation.
F3. Integrating risk assessment and management (consistent exposure assessments for humans and wildlife; risk integration for radiation and other stressors)	An integrated assessment and management approach will enable 'radiation protection' to make more balanced decision as it will take in the 'whole-picture' rather than making individually for human, wildlife, radiation, chemicals etc. It also represents a more defensible approach when communication to stakeholders (including the public).

3.7. Challenge G – Optimise emergency and recovery preparedness and response

In nuclear or radiological emergency management including accidental exposures, medical follow-up and long-term recovery the radiological impact assessment is of prime importance and demands the improvement, development and customisation of several new methodologies and advanced tools. Among them, we should consider advances in atmospheric, aquatic, terrestrial and urban dispersion models, food chain models and dose assessment models, individual monitoring of internal and external exposures and dose reconstruction and finally monitoring of the different environmental compartments, food and goods.

One of the future challenges is to develop and combine different modelling and monitoring techniques (including data assimilation techniques) to improve the predictions of the impact of an accident. Besides advancements in operational monitoring of dose rate values, nuclide-specific information and data on ground and air contamination levels, another emerging challenge would be to integrate measurements or assessments made by the public. Medical follow-up of (potentially) exposed people, depending on the received dose, requires further improvements in biodosimetry, internal and external dosimetry, dose reconstruction techniques and methods and optimised measures to reduce contamination and health effects.

To manage the radiological situation in a holistic way, and in order to better build and implement countermeasure strategies at different time frames (preparedness, response, recovery), there is a need for improved understanding of countermeasures. This includes the development of countermeasures and countermeasure strategies as well as their lifting in time. Important issues to be addressed are among others development of radiological criteria (notably, Operational Intervention Levels (OIL)), effective decontamination strategies (human & environmental), and waste handling from an accident. Improved mechanistic (process based) models will aid in better predicting where countermeasures will be required, the effect of some countermeasures in different geographical areas and also the likely length of time countermeasures will be required. It is also evident that countermeasure strategies have to deal with indirect health consequences, economic, societal and ethical aspects including the environmental characteristics.

An inclusive design and evaluation of countermeasure strategies requires the involvement of all actors, including the public in all phases (preparedness for and recovery from accidents), especially those with off-site consequences. However, the stakeholder engagement process as such is a challenge that requires further developments in the participatory processes in emergency and recovery situations. Furthermore, nuclear or radiological emergency response and recovery requires decisions to be made with high uncertainty in some critical parameters. This needs advanced decision science, situation awareness informatics and the use of big data.

Effective communication strategies during the preparedness, emergency and in the post-accident phases - even with uncertainties - are a key challenge for the success of any measure as they contribute to the development and maintenance of trust between experts, authorities and the population, helping to better implement countermeasures and manage the recovery.

Many of these topics are region-dependent. Therefore, preparedness should take into account accurate local environmental descriptions of the potential sites of nuclear or radiological emergencies. Models of the surrounding environment describing e.g. the population density, biosphere, geosphere and weather conditions should be readily available as real-time dose reconstruction and impact assessment will be needed at the time of the event to provide decision-makers with recommendations for countermeasures. Harmonisation of models across Europe, guidance, including in the availability of tools and expertise and preparedness, especially in certain areas of increased environmental and health vulnerabilities, emergency response and recovery and lessons learnt during and post the incident, would decrease the negative impacts when accidents or incidents occur. Mutual benefit can be obtained by collaboration with relevant security-related research.

The major issues (‘game-changers’) to resolve with potential impact to the radiation protection system and or practice in this area are:

Game Changers	Potential impact to the radiation protection system and/or practice
G1. Change of radiological impact assessments, decision support and response and recovery strategy by Artificial Intelligence (AI) and big data	With AI and big data, new methods for radiological impact assessment, a new DSS and improved response and recovery strategies can be developed, allowing for example the end user to define his or her objectives/goals and the system identifies the best possible strategies to achieve the specified objectives/goals with pros and cons. AI would also allow all stakeholders to evaluate the results in a more comprehensive way as all available information – needed by the AI – is available and can be searched by big data analysis approaches. This new approach requires research in the following areas: • Use of AI and big data in radiological impact assessments and measurement strategies; • Development of a new DSS that uses AI and big data capabilities to better guide the end user in countermeasure strategy definition;

	• Databases with historic and scenario information as starting point for decision making in new events, needed for the AI to learn; • Improved communication/dialogue with stakeholders due to better information availability; • Development of methods to combine uncertainties (e.g. Aleatory, Epistemological, Computational) with AI learning mechanisms.
G2. Further development of risk assessment and risk management approaches, technological capabilities to cope with novel threats and accident scenarios arising from new and future nuclear and radiological technologies, including further development of monitoring and dosimetry techniques	With the evolution of new civilian and military nuclear and radiological technologies and changing global and regional threats, risk assessment and risk management must evolve as well. In this respect, event scenarios, improved early detection, source inversion modelling and new methods to develop countermeasure strategies – based on indicators – are required. Research areas requiring attention are: • Event scenarios, including assessment of potential source terms and evolution of events; • Inverse modelling, data assimilation; • Monitoring strategies with mobile and advanced monitors, relying on citizen science approach and providing early detection of threats; • Combination of monitoring (including citizen monitoring) and simulation of an updated operational picture; • Development of indicators for strategies that can be applied even with little information on the affected area; • Establishment of dialogue/communication with decision makers and concerned stakeholders to challenge the proposed approach on risk assessment and risk management.

3.8. Challenge H – Radiation protection in society

Significant progress has been made on the inclusion of social sciences and humanities insight to the radiation protection field. Work remains to improve further integration between the technical content and the societal context within which RP operates. Therefore, research and innovation in radiation protection needs to be better aligned with the values, needs and expectations of society in order that scientific research can inform decision making more effectively and for innovations to be responsive to, and acceptable by, societal need. The character of social science and humanities research requires that attention to the Social Science and Humanities (SSH) research priorities is essential across all scenarios and is of relevance over all previously stated Challenges.

Without effective means for RP research to reach societal actors, (stakeholders, policy makers, publics) RP knowledge and innovations will fail to generate societal benefits. Concurrently, without openness to inputs from societal actors' values and perspectives, the RP knowledge and innovation communities will fail to address social concerns and political priorities. Thus, meaningful interactions between the technical and societal spheres are essential. Core SSH research concerns, therefore, relate to: defining, building and maintaining effective, two-way communications structures and cultures; development of the processes necessary for relationship and trust building; formulation of new approaches to inclusive governance; and development of novel forms of engagement to reach all relevant communities.

The RP community has to consider the social and ethical justification of exposures to ionizing radiation, under all circumstances, and, accordingly, to develop appropriate radiation protection cultures. The organisation of radiation protection research and the formulation of its policies are shaped by multiple factors (economic priorities, cultural values, institutional interests, stakeholder negotiation, the exercise of power) and these require constant, critical examination and for reflexivity within communities to be enabled. In line with global calls for Responsible Research and Innovation, radiation protection culture should support a reflexive, inclusive and anticipatory stance within the science, technology and innovation communities of the radiation protection field. Core SSH research priorities therefore include: characterization of existing structures, cultures and processes; development of novel methodological approaches to take account of socio-technical integration; and advancement of an open and transparent, anticipatory research culture among RP communities.

The major issues (game changers) that would have a substantial impact on the radiation protection system are:

Game Changers	Potential impact to the radiation protection system and/or practice
H1. Better alignment of research and practice in RP with the values, needs and expectations of society. This will be achieved through: - Effective research translation mechanisms; - Development of systematic approaches to inclusion of societal dimensions at all levels of the RP system and - Methodological innovation enabling transdisciplinarity in radiation protection research.	Effective research translation mechanisms will ensure generation of robust radiation protection knowledge that aligns societal and technical dimensions. This will result in new theory on knowledge exchange mechanisms between technical and societal spheres to underpin new practice; empirical evidence of the effectiveness of, and limitations to, current communicative structures and cultures to identify areas of action; and highlighting novel forms of citizen engagement, including advancement of innovative technological interventions. Development of systematic approaches to inclusion of societal dimensions at all levels of the RP system will ensure that RP research, policy and practice are responsive to the values and interests of diverse actors. Development of mechanisms for integration of responsible research and innovation within RP communities and integration of models of anticipation into RP practice will enable development of reflexive research cultures within RP and improve radiation protection. Improvements in the research, governance and practice of radiation protection will emerge that are based on advancements in the co-production of RP knowledge between science and society. This will inform RP policy and practice, through consideration of the ethical and social dimensions of the RP system, including attention to cultural diversity. Methodological innovations will enable collaboration between different disciplines and between different societal actors in transdisciplinary research environments. Development of social indicators will support the evaluation of the alignment of research and practice in RP with the values, needs and expectations of society.

3.9. Summary list of game changers

In Table 3 a summary list of game changers defined in the different research challenges is presented, together with the radiation protection research platforms involved and the potential end users interested in the execution of the research.

Table 3 Game Changer list, involvement of radiation protection research platforms and intended end users

Game Changer No	Game Changer title	RPR platforms involved	End users
A1	Define the risks of non-cancer diseases at low and intermediate dose levels (100 - 500 mGy and below).	MELODI	UNSCEAR, ICRP, IAEA, legislators, and regulators
A2	Integration of epidemiological estimates of cancer risk with a more complete understanding of radiological disease pathogenesis to improve cancer risk assessment	MELODI, EURAMED, SHARE	UNSCEAR, ICRP, IAEA, legislators, and regulators
A3	Characterisation and quantification of variation in radiation response and risk between population sub-groups/individuals due to genetic factors, sex, co-morbidities, dedicated exposure of diseased areas in patients, environmental and lifestyle factors and the interactions between these depending on dose-levels.	MELODI, EURAMED	UNSCEAR, ICRP, IAEA, legislators, and regulators
A4	Define how the temporal and spatial variations in dose delivery affect the risk of health effects following radiation exposure.	MELODI, EURADOS	UNSCEAR, ICRP, IAEA, legislators, and regulators
B1	To improve the understanding of spatial correlations of radiation interaction events by improved measurement and simulation techniques.	EURADOS, MELODI	UNSCEAR, ICRP, IAEA, legislators, and regulators
B2	To quantify correlations between track structure and radiation damage	EURADOS, MELODI	UNSCEAR, ICRP, IAEA, legislators, and regulators
C1	Lifting the controversy with regard to the effects on wildlife reported in the Chernobyl and Fukushima exclusion zones	ALLIANCE, MELODI, EURADOS, NERIS, SHARE	UNSCEAR, ICRP, IAEA, Legislators, and regulators
C2	Determine the effects of radiation on ecosystem functioning	ALLIANCE, MELODI, EURADOS, NERIS, SHARE	UNSCEAR, ICRP, IAEA, legislators, and regulators
D1	Develop new medical applications or optimize existing ones depending on disease related applications e.g. interventional procedures, CT based approaches, targeted therapies in nuclear medicine and particle based therapies, to improve patients protection relying on corresponding improved dosimetry procedures for individual patients	EURAMED, EURADOS, MELODI	Health care providers, legislators and regulators

D2	Application and development of AI methods to improve patient protection relying on suitable clinical data structures and taking into account the limits of the use of AI especially in the medical field.	EURAMED, SHARE	Health care providers, legislators and regulators
D3	Investigating key challenges and problems for the transfer of developments into clinical practice, evaluate conditions leading to large differences throughout Europe, defining standards for justification of applications depending on individual patient characteristics and benefit-risk evaluations of procedures, a dedicated education guaranteeing the best possible radiation protection for patients	EURAMED, EURADOS, SHARE	Health care providers, legislators and regulators
E1	Development of biokinetic models and personalised dosimetry that will lead to the improvement of the assessment of internal exposure	EURADOS, EURAMED, MELODI	UNSCEAR, ICRP, IAEA, legislators, and regulators
E2	The development of real time practical individual dosimetry of workers by harnessing the developments in new connected technologies	EURADOS, EURAMED	Operators, regulators
E3	Development of a practical neutron personal dosemeter	EURADOS	Operators, regulators
F1	Getting a robust prediction of the human food chain radiological contamination, for an integrated dose and risk assessment of (post)emergency situations	ALLIANCE, MELODI, EURADOS, NERIS, SHARE	UNSCEAR, ICRP, IAEA, legislators, and regulators
F2	Identifying and quantifying the key processes that influence radionuclide behaviour in existing environmental contamination situations	ALLIANCE, MELODI, EURADOS, NERIS, SHARE	UNSCEAR, ICRP, IAEA, legislators, and regulators
F3	Integrating risk assessment and management (consistent exposure assessments for humans and wildlife; risk integration for radiation and other stressors)	ALLIANCE, MELODI, EURADOS, NERIS, SHARE	UNSCEAR, ICRP, IAEA, legislators, and regulators
G1	Change of radiological impact assessments, decision support and response and recovery strategy by Artificial Intelligence and big data	NERIS, ALLIANCE, SHARE, EURADOS	UNSCEAR, ICRP, IAEA, legislators, regulators, local authorities
G2	Further development of risk assessment and risk management approaches and technological capabilities to cope with novel threats and accident scenarios arising from new and future nuclear and radiological technologies	NERIS, ALLIANCE, SHARE, EURADOS	UNSCEAR, ICRP, IAEA, legislators, regulators, local authorities
H1	Better alignment of research and practice in RP with the values, needs and expectation of society, through effective research translation mechanisms, development of systematic approaches to inclusion of societal dimensions at all levels of the RP system and methodological innovation enabling transdisciplinarity in RP research	SHARE, MELODI, EURADOS, NERIS, ALLIANCE, EURAMED	Radiation protection community and society

4. Graphical presentation of the joint research challenges and game changers

In order to estimate the type of research needed and the time frame needed to achieve the goals, the joint research challenges are presented in a graphical way. The game changers are accompanied by the number as presented in Chapter 3 and in Table 3, to show how related research could be planned when resources are available.

Some of the research shown in one particular graphical presentation may be strongly related with research in another joint research challenges. Non-exhaustive examples are studies related to individual sensitivity in Game Changer A3, which is also relevant in challenge D, or challenge G that strongly relies on new knowledge related to various other challenges. These examples show the need of concerted actions and strong collaboration between the different research fields in radiation protection.

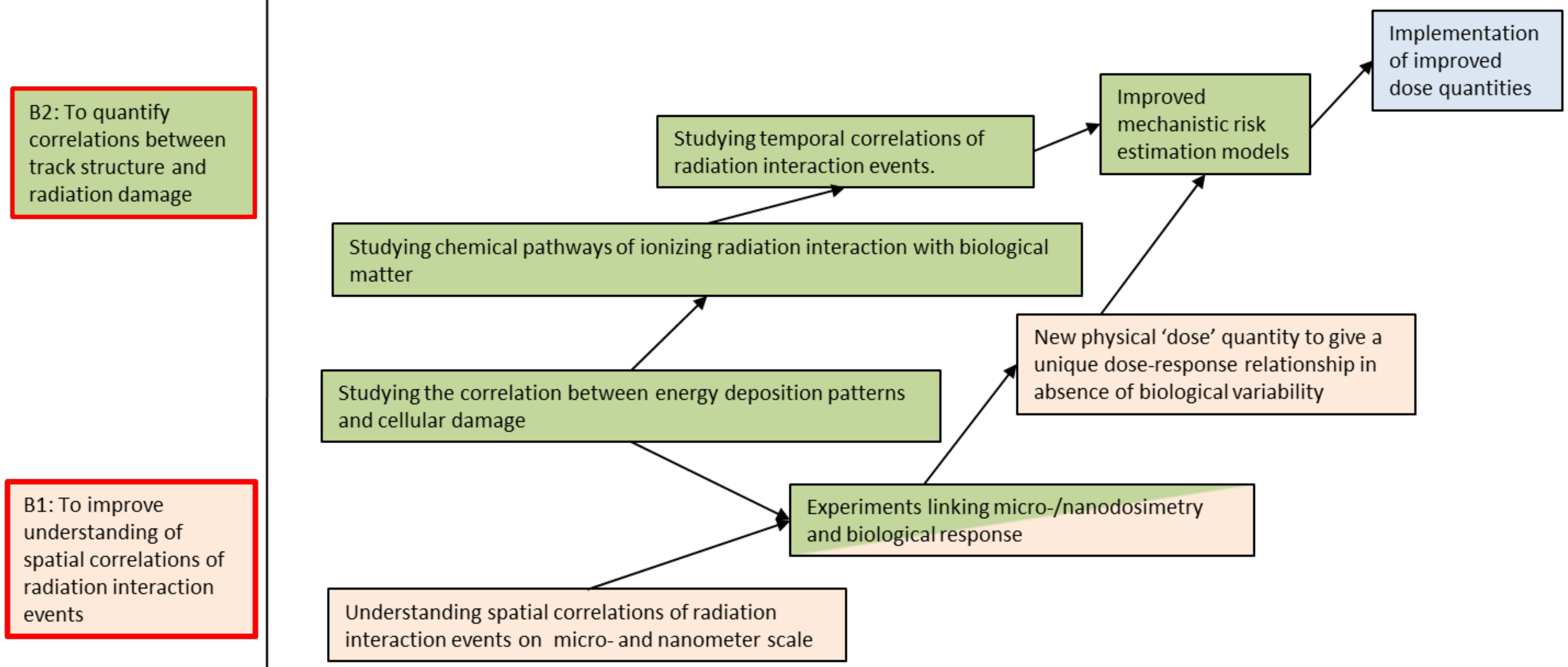
The timelines of the graphs are different, according to the ability to plan research in the different fields. The timelines should be considered as rough guides, because the implementation of the roadmap depends on the resources available as presented in Chapter 5, and on external factors such as advances in research outside the radiation protection area, or on changes in the society or the environment.

Challenge A – Understanding and quantifying the health effects of ionising radiation exposure

Drivers /Exposure situations	Where present at low doses, these risks could lead to re-consideration of dose limits as well as impact on tissue weighting factors, radiation weighting factors and calculation of detriment. A move to a more individualised approach to protection might be required. Relevant to all exposure situations
Game changers	
A1: Non-cancer disease risks – quantification and mechanistic understanding	Building and maintaining relevant cohorts; Periodic analyses; Improved risk quantification Targeted studies of potential contributory mechanisms; Building the relevant AOPs Target cell identification and quantification; Application to improve risk estimation
A2: Integration of epidemiological estimates of cancer risk with understanding of radiological disease pathogenesis	Studies of specific pathways; Identification and quantification of target cell populations; Integration into AOP Identification of mutational signatures and other biomarkers of radiation cancers Development of models to integrate mechanisms and epidemiology; Application for risk assessment Maintaining established cohorts; Evaluation of existing non-radiation cohorts; Periodic analyses
A3: Characterisation and quantification of the variation of responses and risk between population sub-groups/individuals due to genetic factors, environmental and lifestyle factors	Tissue reactions: clinical studies; mechanistic studies Late developing tissue reactions: Definition of mechanisms; population studies Cancers: continuation and initiation of epidemiological studies of risk modification experimental studies of risk modification → Development of predictive assays
A4: Define how the temporal and spatial variations in dose delivery affect the risk of health effects following radiation exposure	Improved understanding of inter and intra-organ dose distribution; Evaluation of W_T Identification of improved cohorts for epidemiological investigation – periodic analyses Experimental investigation of radiation quality effects; Biophysical modelling of dose and effects; Assessment of W_R
Required science and technology	Science: Improved epidemiological cohorts, evaluation of non-radiation cohorts, animal models of radiation disease, high-quality exposure assessment and dosimetry, application of radiobiology, molecular and cell biology, omics Technology: Low dose/dose-rate exposure facilities, advanced statistical methods, well curated bio-sample collections bioinformatics
	2020 — 2030 — 2040

Challenge B – Improving the concepts of dose quantities

Drivers /Exposure situations	Absorbed dose is not an adequately detailed description of the energy deposition for correlation with biological consequences because (a) the dose-response relation for a particular biological system depends on the radiation parameters (e.g., type, energy) and the stochastic pattern of energy deposition, (b) different biological systems have different susceptibilities for producing radiation-induced effects, (c) many biological processes are non-linear and (d) biological effects may differ depending on the temporal pattern of exposure.
Game changers	Over-all goal of challenge B: To improve protection and operational quantities used in dosimetry



Needed Science and Technology	1. Advanced detectors for measuring ionising radiation interaction at the micro- and nanometer scale 2. Metrological methods for improved detection of radiation-induced biological endpoints with automated assays 3. Improved multi-scale Monte Carlo simulations for predicting radiation-induced damage

2020 2025 2030

Challenge C – Understanding radiation-related effects on non-human biota and ecosystems

Drivers /Exposure situations

The need for an explicit demonstration of the protection of the environment from radioactive releases is now recognized. However, the available knowledge is related to the risk to individual organisms, whereas populations, ecological function and biodiversity are more relevant from a management perspective. There is still scientific disagreement on the actual extent of the radiation effects on wildlife populations in contaminated areas.

Game changers

C1: Resolving the controversy with regard to the effects on wildlife reported in the Chernobyl and Fukushima exclusion zones

Characterize the influence of exposures on populations in contaminated environments

- Re-interpretation of data on long-term ecological effects of radiation
- Field studies, transplant experiments
- Multi- trans-generational effects experiments
- Comparison between field and lab studies
- Understand hereditary & adaptation effects

Identify the key factors determining the variation in populations' sensitivity to radiation

- Variation due to genetic & metabolic factors
- Influence of species life-cycle specificities
- Population-effect benchmark derivation
- Variation due to environment & behavior
- Species Sensitivity Distribution update

Identify and validate biomarkers of exposure and effects that are relevant at the population's level

- Primary mode of action of IR – Identify biomarkers
- Adverse Outcome Pathway and Systems Biology approach
- Biomarkers testing
- Biomarkers toolbox available for application

C2: Determine the effects of radiation on ecosystem functioning

- Effects at community level (micro- meso-cosmos) & exposure characterization under realistic conditions
- Ecological models for risk assessment
- Ecosystems dynamics modelling
- Impact on ecosystem services

Required science and technology

Science: field effect data, laboratory models to identify radiation effects at the population/community level, high-quality exposure assessment and dosimetry, application of omics and AOP for the identification and validation of biomarkers
Technology: Well curated and shared datasets and sample collections from Chernobyl and Fukushima exclusion zones, Low dose/dose-rate exposure facilities, Advanced statistical methods

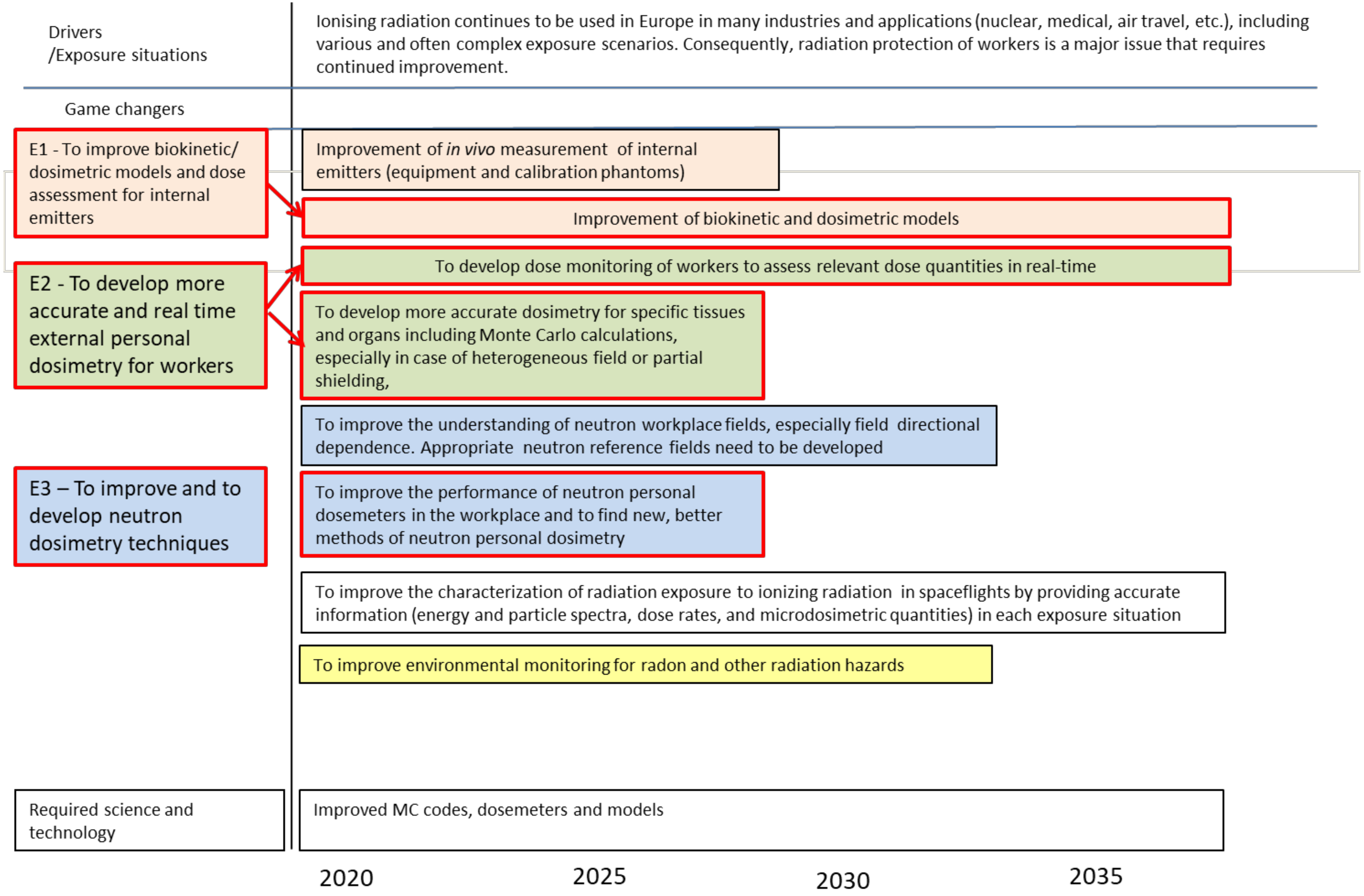
2020 | 2025 | 2030 | 2035 | 2040

Challenge D – Optimizing medical applications of ionizing radiation and harmonizing practices throughout Europe

Drivers /Exposure situations	It is of great importance to optimise the medical applications of ionising radiation for the diagnosis and treatment using individualized approaches and harmonise practises throughout Europe especially with respect to the protection of human health from the harmful effects of ionising radiation and with respect to the potential benefit of the use of ionising radiation for the individual patient.
Game changers	
D1: To develop / optimize medical applications of ionizing radiation using personalized dosimetry	Development of personalized dosimetry in diagnostic and interventional radiology, new or optimized interventional procedures and CT-based approaches, targeted therapies in nuclear medicine and particle based therapies to improve patient radiation protection. These optimized methodologies can reduce exposure while maintaining or even improving clinical outcome and harmonize medical radiation protection within Europe. Personalized dosimetry in imaging — New optimized approaches in imaging and radiation therapy — Medical RP harmonization in Europe
D2: Application and development of AI methods to improve patient radiation protection	Systematic and organized collection of big data for medical radiation protection, development of suitable national and European data structures for AI methodologies, development of AI tools to improve patient and staff radiation protection, understanding the limits of the use of AI in the medical radiation protection field. Development of imaging and dose biobanks — Development of AI methodologies — Wide application of AI in clinical practice to optimize procedures
D3: To transfer research developments into clinical practice and define standards for exposure justification	Investigating key challenges and problems for the transfer of developments into clinical practice, evaluate conditions leading to large differences throughout Europe, developing accreditation processes based on quality and safety, defining standards for justification of applications depending on individual patient characteristics and benefit-risk evaluations of procedures. Improved radiation risk appraisal — Development of accreditation processes — Clinical Decision Support in European hospitals for referral guidelines
Required science and technology	Physical and biological models and criteria for medical use of ionising radiation; Methods for individualized dosimetry, QA methodology for AI methods; New radiation generation technologies.

2020 2024 2028 2032 2036 2040

Challenge E – Improving radiation protection for workers

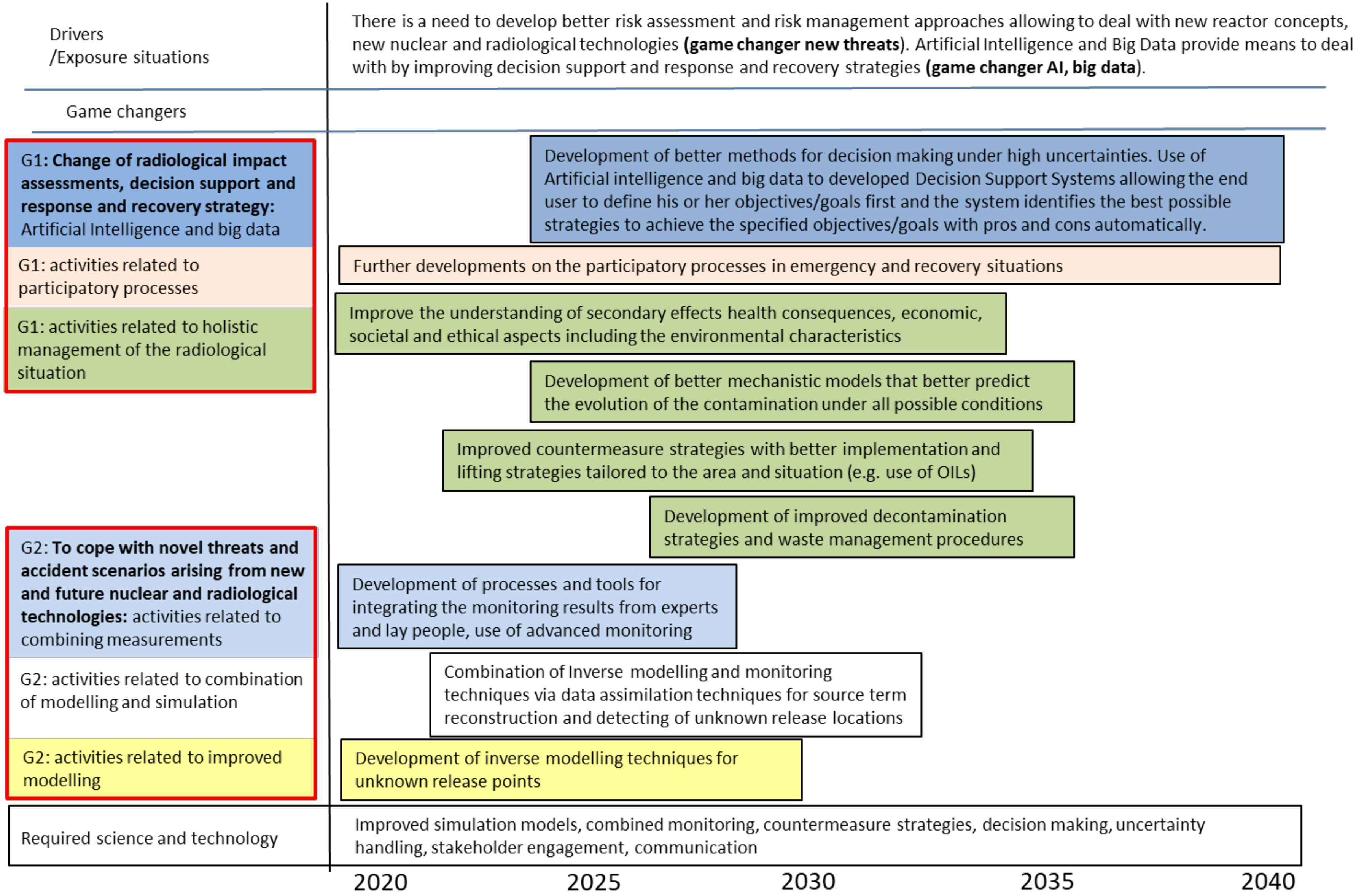


Challenge F – Integrated approach to environmental exposure and risk assessment from ionising radiation

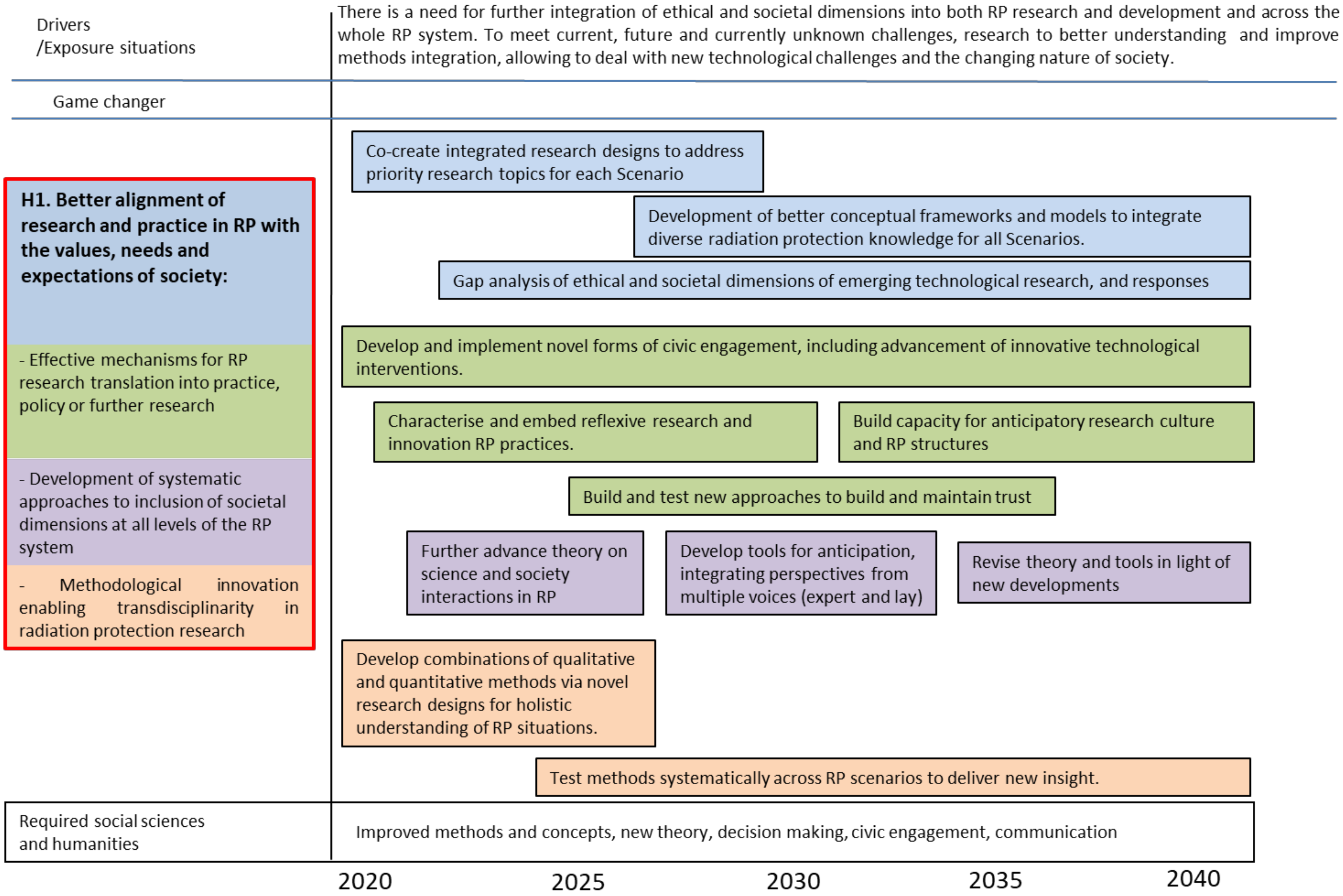
Drivers /Exposure situations	Holistic approaches to risk assessment are needed to ensure sustainable and safe use of radioactive substances and to protect both human and ecosystem health. The development of improved international guidance on the management of legacy sites, that often represent complex "objects" to be managed, requires a multistage process including site characterization, definition of objectives for remediation, impact and risk assessment, and evaluation and selection of remedial options.
Game changers	
F1: Deriving a robust prediction of radiological contamination in the human food chain, for an integrated dose and risk assessment of (post-)emergency situations	• Meta-analysis and data re-interpretation, data management • Identify most promising models and adapt • Upgraded models for dispersion and transfer assessment in marine and surface water ecosystems • Upgraded models dispersion and transfer assessment in terrestrial ecosystems (agricultural, forestry, natural and urban) • Resultant models applicable in any relevant environment, time-evolution, food type
F2: Identifying and quantifying the key processes that influence radionuclide behaviour in existing environmental contamination situations	• Meta-analysis and data re-interpretation and advanced data management • Identify most relevant (mechanistic) models and adapt • Upgraded models for dispersion and transfer assessment in relevant environments/ecosystems • Models for accurate dose impact and assessment • Guidance for the sustainable management (including remediation approaches) of contaminated sites
F3: Integrating risk assessment and management (consistent exposure assessments for humans and wildlife; risk integration for radiation and other stressors)	• Identification stages of different assessment processes to be integrated and structure/construct datasets, models, DSS • Dispersion, transfer, impact assessment models (F1 & F2 outputs) • Integrate uncertainty and variability from exposure and effects characterisation into risk characterization • Integrate human and environmental protection frameworks • Integrate the risk assessment frameworks for ionising radiation and chemicals (eg. msPAF, « exposome » approach) • Provide a multi-criteria perspective including decision support systems for an optimised decision-making
Required science and technology	Uncertainty consideration in all its dimensions (monitoring, process knowledge, conceptual models, parametric, societal factors), Advanced statistical methods, advanced data management, Well curated and shared environmental monitoring datasets for models validation

2020 2025 2030 2035 2040

Challenge G – Optimise emergency and recovery preparedness and response



Challenge H – Radiation Protection *in* Society



5. Resources for radiation protection research

5.1. Human resources: More than 200 organisations contribute to the European joint radiation protection research

A rough estimate of the research groups currently active in the integration efforts within radiation protection research in Europe can be obtained by counting the members of the European radiation protection research platforms and the research groups involved in EJP CONCERT (Annex 1). However, the list in Annex 1 is not exhaustive, and in particular many additional universities have research groups active in radiation protection research.

The platforms succeeded to gather most research groups active in their fields of research in a successful attempt to combat fragmentation of research and to pool a critical mass. More than 170 organisations are members in the six thematic platforms (associations), and more than 90 entities are involved in CONCERT. In total more than 200 organisations contribute to European joint radiation protection research. They have joined forces to create and update the strategic agendas and to carry out RP research. One third of the organisations listed in Annex 1 are universities (72/210). Within CONCERT, organisations have been mobilised in most European countries (25/28); only small countries such as Cyprus, Malta and Luxembourg apparently have not yet joined the European brainstorming task forces permitting an inclusion of their national research activities related to radiation protection.

In Table , a summary of the number of members of the different platforms is presented. It must be noted that the membership structures are different. Overall, the institutional members include research institutes, universities, National bodies, funding agencies, hospitals, associations, SMEs, International Organisations and a few individuals.

Table 4 Members of the different radiation protection research platforms. The institutional and university members represent groups of researchers active in the relevant radiation protection research disciplines. (*) Included in the category members representing multiple researchers are research institutes, universities, national bodies, hospitals and SMEs.

Platform	members representing overarching associations	members representing multiple researchers (*)	Individual members
MELODI	4: ESR, ESTRO, EANM, KVSF	40 Europe + 1 Canada	9 (7 + 2 honorary)
EURADOS	0	74	620
NERIS	1: CEPN	54 Europe + 9 Ukraine, Belarus, JP, Russia,	0
ALLIANCE	0	30	0
EURAMED	5: EANM, EFOMP, EFRS, ESR, ESTRO	7	
SHARE	1: CEPN	21	2

In this first attempt ever to provide an overview of human resources available in Europe for radiation protection research, it is not possible to obtain an exact number of researchers. However, within the different domains together, a few thousands of researchers devote at least part of their working time to radiation protection research.

Whereas the EURATOM funded projects have supported the integration between research disciplines and collaboration between the different Member States, Table and Annex 1 demonstrate through the existence of numerous research groups in institutes and universities that the majority of resources for radiation protection research is provided by their Member States. Therefore, it can be deduced that the sustainability of the research community is mostly provided by national funding sustaining research infrastructures, supporting lifelong research positions and running education programmes.

Annex 1 demonstrates the broad range of entities engaged in radiation protection research. As envisaged by the HLEG in 2009, the initial idea was to bring together national funding bodies, for the establishment of a trans-national organisation capable of ensuring an appropriate governance of research in this field, and a scientific strategy capable of structuring future research in the most effective way, taking into account available resources. Since then, it has become clear that very few of the national academies fund radiation protection research. Such funding is mainly channeled via the institutional budgets and via special budgets of the responsible ministries. While there are arrangements and dedicated programs for nuclear safety research in countries using nuclear energy, similar funding arrangements often do not exist within the radiation protection research area. Not all Member States have a national funding organization or other national programmes covering radiation protection research. This is a serious problem which is jeopardizing co-funding activities on the European level or is even inhibiting participation of research partners from specific countries to participate in this kind of European programmes.

5.2. Future resources needed for the joint roadmap

The practical implementation of the joint roadmap for radiation protection research will strongly depend on the resources available. The different Game Changers defined in Chapter 3 are graphically presented **with timelines that are subject to the availability of funding and other resources. The joint roadmap is** therefore a living document and will be updated by time. New challenges may arise that need attention while some questions may be solved sooner than anticipated.

A. Needs based on game changers

The game changers were derived from the joint research challenges from the perspective of the societal benefit, i.e. protecting the people, the environment, the society and future generations from the harmful effects of ionizing radiation, without unnecessarily limiting the application of radiation for the benefit of mankind. These game changers are highly multidisciplinary and require a supranational coordination and collaboration. Therefore, funding at European level is essential. Next to European alignment, the integrative approach may benefit from national networks, such as CORES, PEPRI and the BCRPR. These networks can strengthen the efficacy of the nationally funded research groups in the different types of institutes / universities, which are the basic foundations of radiation protection research, in need of continuous and predictable funding to ensure persisting engagement and attraction of experts and responsible for keeping up to date their infrastructures.

Whereas EURATOM is the core funding programme of nuclear and related research, the research proposed within the game changers has a broader societal perspective and some areas are strongly related to domains outside the EURATOM programme. For example, medical radiation protection research shows clear links to the HEALTH programme, topics requiring artificial intelligence would benefit from collaboration with ICT and HEALTH programmes; the radioecology related topics would benefit from collaboration with ecotoxicology or the consequences of climate change; and emergency management and preparedness may benefit from security research programmes. Similar analogies can be found for the basic research disciplines involved in radiation protection research (e.g. bioinformatics, physics, earth sciences, cancer research, etc.). Therefore, it is proposed to allow funding on national and

EURATOM level as core funding, complemented with coordinated co-funding to reach out and collaborate with related RTD programmes outside EURATOM.

B. Development of the research community: the need for education and training

The Joint Roadmap lays out an ambitious programme of radiation protection research over the next twenty to thirty years. The subject has been developing in breadth since the beginning of the use of radiation for medicine and then power generation. The early science of radiation protection was mainly limited to the physics of radiation shielding, and experimental radiobiology. The new research has split into six different areas represented by the six platforms, and has embraced new technologies including bioinformatics, powerful computing, and big data. This places great demands on the skills and resources of the research community. But, as well as changes in the scientific domain, the demographics of the community have been changing, both due to population aging, and changing pressures in the work environment. Pioneering researchers are now retiring; the subject is no longer as fashionable as it was during the infancy of nuclear power; students are struggling to find secure career appointments against competition from health and environment research.

All these factors point to the same directions: to carry out the research programmes called for here, there must be a coordinated and strongly supported built-in programme of education and training to maintain and develop the human resources. This programme must be broad in scope: attracting new entry-level students into the topic area, providing project opportunities for MSc and PhD students, continuing professional development of researchers, support for researcher career paths, and knowledge management to ensure the researchers of today benefit from the experience and knowledge of the previous generation as well as current developments.

Over the last ten years, through the Network of Excellence DoReMi and the European Joint Programme CONCERT, the EC has funded an annual programme of short courses giving students a free hands-on introduction to research topics. It has also provided travel grants to enable students and early career researchers to present their work at conferences, attend courses, or go for exchange visits to laboratories. A firm long-term commitment for this type of support will be essential. Support should also be given to EURAYS (European Radiation Research Association for Young Scientists). This is a network for early career researchers in radiation protection that was originally set up in 2013 on a pro bono basis and is now being restructured to provide sustainability. An essential part of sustainability will be attracting supporting sponsorship to cover costs.

Next to education and training of young researchers entering the field of radiation protection research there is a need for lifelong learning programmes to enable researchers to enter emerging research fields within the course of their research careers. In addition, the education and training programmes within radiation protection research are part of the dissemination needed to bring results of the research to the end users. In this perspective, we also need to link E&T activities in research with E&T organized for radiation protection practice. Education and training activities are therefore inherent to the implementation of the joint roadmap, providing research for an improved radiation protection system and practice.

C. Infrastructures under fair policies

Inventory of European infrastructures and future needs having revealed that most necessary infrastructures are already available somewhere in Europe or other countries. We need to make better use of existing competences and research infrastructures in Europe. The current challenge is to facilitate their access by increasing their visibility, to favour their sustainability beyond national short-term economic constraints and to support exchange visits for their use.

Next steps will rely into further harmonisation of quality standards, practices and protocols in relation to the use of infrastructure including the implementation of intercomparisons. Huge efforts will be dedicated to sample/data acquisition and sample/data storage with the aims to re-use of archived materials. We will propose trans-national agreement on a strategic work plan for maintenance, updating, mutual use and new needs of suitable infrastructures. Meanwhile, education and training actions will promote the use of European research infrastructures the advantage of using newer, larger, faster, more powerful infrastructures although not at the bench of each user.

6. Implementation of the joint roadmap: vision of the joint roadmap working group

The implementation of the lines of research described in the Joint Roadmap and the graphical representations in Chapter 4 call for coordination of resources and timely investments. The members of the RP research platforms represent a major resource of human competence as well as research infrastructures, focused on joint objectives. Based on the obvious success of the radiation protection research platforms and the SRAs, and on the experiences on integration of research within FP7 (mainly within the DoReMi, OPERRA and COMET projects) and H2020 (mainly within EJP CONCERT and MEDIRAD), we propose a long-term call planning system to turn the joint roadmap into reality. Efforts to integrate the research community on a national and European level should be continued and additional efforts should be devoted to international cooperation on topics of mutual interest, in order to bring together the critical mass of scientists and knowledge. On the other hand, the implementation actions should be compatible with the different financial structures in European Member States, the European level and should allow sustainability of research activities within and outside Europe.

Despite the success of the RP platforms, joint planning between the national programmes and the Euratom programme have not kept in step with each other. Requirements for national co-funding in EURATOM research has been a major issue due to the incompatibilities of EU and national rules, and the highly variable national rules. The funding rules of the European Commission and of Member States should be made compatible in a way that discrimination against research partners solely due to co-funding problems in Member States is avoided.

Open, competitive calls to organize research in radiation protection according to the joint roadmap need to be pursued. They pave the way to excellent science and to fair chances for research groups from all kind of research institutions to participate in radiation protection research in Europe based on their scientific merits. Scientific excellence should remain the major and most important criterion in peer reviewing of proposals. Further attention should be paid to the preparation of call texts and conditions in order to address special European requirements and needs in radiation protection and the added value of the European integration efforts. The management of calls by an administration that is isolated from the research community like in EJP CONCERT should be favoured. Evaluation of proposals should be provided by experts free from conflict of interest but having experience in European radiation protection needs.

Whereas EURATOM is the core funding programme of nuclear and related research, the research proposed within the game changers has a broader societal perspective and some areas are strongly related to domains outside the EURATOM programme. For example, medical radiation protection research shows clear links to the HEALTH programme, topics requiring artificial intelligence would benefit from collaboration with ICT and HEALTH programmes; the radioecology related topics would benefit from collaboration with ecotoxicology or the consequences of climate change; and emergency management and preparedness may benefit from research in other accident scenarios or security research programmes. While recognising that there are budgetary constraints to realise joint funding between programmes under separate treaties, this aim should be pursued anyway, for the benefit of science and society. Supporting research on medical radiation protection should not come on the expense of other RP research fields.

To complement the research activities, a strongly directed comprehensive programme of education and training will be needed. E&T is an essential component of the research process. As presented in Chapter 5, an actively supported programme of E&T is needed to develop and maintain the research community. Further to this, all research projects must be required to allocate a proportion of their budget to E&T activities. Horizon 2020 has set a minimum level of 5% and this should at least be continued. The E&T activities would include provision of project opportunities for MSc and PhD students, as well as hosting seminars, workshops, and courses on topics in the research area. E&T is an important element of dissemination and impact creation, providing an outreach to related professionals and stakeholders, both for communicating new knowledge and for seeking feedback. For such a comprehensive E&T programme to function in a coordinated way there must be top-down direction and support. This requires dedicated funding, either as part of an umbrella programme such as an EJP, or as a separate call.

The establishment of a sustainable European radiation protection research programme could be facilitated by (1) co-programming, (2) by a strong European joint programming consortium linked with the wider research community and allowing open calls with co-funding rules that do not exclude any potential partners, and by (3) an institutionalised permanent joint programme secretariat suited for long term challenges and priorities. Beside strong institutional partners from member states responsible for running national radiation protection research programmes and/or funding such programmes, the platforms should be involved to sustain and further improve the network of the radiation protection research community and assessment of state of the art and priority setting. These options need to be investigated thoroughly and the best option selected to meet the needs described in this chapter. Essential elements are open, competitive calls to organize research in radiation protection according to the joint roadmap, the implementation of an independent call management unit operating behind a firewall to restrain undue interference by potential applicants, and inclusion of E&T activities, such as project opportunities for MSc and PhD students. A long-term commitment of EURATOM would allow for the implementation of an ambitious, integrative and sustainable radiation protection research roadmap shaped by societal challenges.

7. Annexes

7.1. Annex 1: List of Platform members and EJP-CONCERT partners

Organization Acronym	**Name Organization**	Category	Country	EJP-CONCERT	MELODI	ALLIANCE	EURADOS	NERIS	EURAMED	SHARE
AIST	National Institute of Advanced Industrial Science and Technology	Research Institute	Japan					1		
AIT	Austrian Institute of Technology GmbH	Research Institute	Austria				1			
ALLIANCE	ASSOCIATION ALLIANCE EUROPEENNE EN RADIOECOLOGIE	Association	France	BEN						
ANR	ANR - Agence National de la Recherche, France	Funding Agency	France	BEN						
APA	Environmental protection agency - Portugal	National Body	Portugal	BEN				1		
APHP	Assistance Publique Hopitaux de Paris	Hospital	France	TP						
AWE	Atomic Weapons Establishment plc.	Research Institute	United Kingdom				1			
Berthold	Berthold Industries	SME	Germany				1			
BfS	Bundesamt für Strahlenschutz, BfS	Research Institute	Germany	Coord/ BEN	1	1	1	1	1	1
CAATS	Centre d'Assurance de qualité des Applications Technologiquesdans le domaine de la Santé	SME	France	TP						
CAM AC UK	University of Cambridge	University	United Kingdom	Subcontract				1		
Cavendish Nuclear	Cavendish Nuclear Ltd	SME	United Kingdom				1			
CC UOI	University of Ioannina	University	Greece					1		
CEA	Commissariat à l'Energie Atomique et aux Energies Alternatives	Research Institute	France	BEN	1	1	1			
CEH	Centre for Ecology and Hydrology (CEH)	Research Institute	United Kingdom	LTP		1				
CEPN	radiation protection R&D center - NPO	Association	France	LTP				1		1
CERAD-NMBU	Centre for Environmental Radioactivity (CERAD)	Research Institute	Norway	LTP	1	1		1		1
CERN	European Organisation for Nuclear Research	International Organization	Switzerland				1			
CESNEF	Politechnico di Milano	University	Italy				1			
CIEMAT	Centro de InvestigacionesEnergéticas Medioambientales y Tecnologicas	Research Institute	Spain	BEN		1	1	1		1

CLOR	CentralneLaboratoriumOchronyRadiologicznej (CLOR)	Research Institute	Poland			1				
CND	Centro Nacional de Dosimetrica	Research Institute	Spain				1			
Collegium Civitas	Collegium Civitas	Research Institute	Poland							1
Controlatom	VincotteControlatom	Research Institute	Belgium				1			
CRIEPI	Central Research Institute of Electric Power Industry	Research Institute	Japan	TP				1		
CTU	CESKE VYSOKEUCENITECHNICKE V PRAZE Czech Technical University	University	Czech Republic				1			
DEMA	Danish Emergency Management Agency (DEMA, Denmark)	National body	Denmark	BEN				1		
Dialogik	Dialogik	non-profit research institute	Germany	TP						
DIT	DUBLIN INSTITUTE OF TECHNOLOGY, DIT	Research Institute	Ireland	TP						
DMI	Danish Meterological Institute	Research Institute	Denmark	LTP				1		
DOSILAB	DOSILAB AG	SME	Switzerland				1			
DOZIMED	Dozimed Ltd	SME	Romania				1			
DSA	Norwegian Radiation and Nuclear Safety Authority	National body	Norway	BEN	1	1	1	1		
DTU	Technical University of Denmark	University	Denmark	LTP				1		
DurhamUni	UNIVERSITY OF DURHAM	University	United Kingdom	LTP						
DWD	Germany's National Meteorological Service	National body	Germany					1		
EANM	European Association of Nuclear Medicine	Association	Austria		1				1	
EEAE	The Greek Atomic Energy Commission	National body	Greece	BEN	1		1	1		1
EFOMP	European Federation of Organisations for Medical Physics	Association	United Kingdom		1				1	
EFRS	European Federation of Radiographer Societies	Association	The Netherlands		1				1	
EIMV	Milan Vidmar Electric Power Research Institute	Research Institute	Slovenia					1		
Else Nuclear	Else Nuclear srl	SME	Italy				1			
ENCONET	nuclear research institute	Research Institute	Croatia					1		
ENEA	National Agency for New Technology, Energy and the Environment	National body	Italy	BEN	1		1	1		

ENSTII	EUROPEAN NUCLEAR SAFETY TRAINING AND TUTORING INSTITUTE	Association	France	LTP						
EPA	Environmental Protection Agency	National body	Ireland	BEN		1		1		
ESR	European Society of Radiology	Association	Austria		1				1	
ESTRO	the European SocieTy for Radiotherapy & Oncology,	Association	Belgium		1				1	
EURADOS	EUROPEAN RADIATION DOSIMETRY GROUP	Association	Germany	BEN			1			
EURAMED	EUROPEAN ALLIANCE FOR MEDICAL RADIATION PROTECTION RESEARCH (EURAMED)	Association	Austria	BEN					1	
Faculty of Medicine	Faculty of Medicine, University of Osijek	University	Croatia				1			
FANC	Federal Agency of Nuclear Control	National Body	Belgium					1		
FCT	FCT - Fundacao para a Ciencia e Tecnologia / Foundation for Science and Technology, Portugal	Funding Agency	Portugal	BEN						
FEERCObninsk	Federal Environmental Emergency Response Centre of Roshydromet	National Body	Russia					1		
FMBA	Federal Medical Biophysical Centre	Research Institute	Russia				1			
FMU	Fukushima Medical University	University	Japan	TP				1		
FOPH	Federal Office of Public Health	National body	Switzerland	BEN				1		
FSS-Uni-LJ	UNIVERZA V LJUBLJANI	University	Slovenia	LTP						
FU	Fukushima University	University	Japan			1		1		
GIG	Główny Instytut Górnictwa (GIG)	Research Institute	Poland	BEN		1				
GRS	Global Research for Safety - non profit organisation	Research Institute	Germany					1		
GSI	GSI HELMHOLTZ ZENTRUM FUER SCHWERIONENFORSCHUNG GMBH	Research Institute	Germany	LTP						
GU	University of Gothenburg	University	Sweden					1		
GUF	Goethe-University, Frankfurt am Main	University	Germany	TP						
HMGU	Helmholtz Zentrum München, Deutsches Forschungszentrum für Gesundheit und Umwelt	Research Institute	Germany	BEN	1	1	1			
HU	Hiroshima University	University	Japan					1		
HUG	HôpitauxUniversitaires de Genève	Hospital	Switzerland	TP						
HZDR	Helmholtz-Zentrum Dresden-Rossendorf (HZDR)	Research Institute	Germany	LTP		1				

IAEA	International Atomic Energy Agency	International Organization	Austria				1				
IFA	IFA - Institutul de FizicăAtomică, Romania	Research Institute	Romania	BEN							
IFIN-HH	INSTITUTUL NATIONAL DE CERCETARE - DEZVOLTAREPENTRUFIZICA SI INGINERIENUCLEARA "HORIAHULUBEI" (IFIN-HH)	Research Institute	Romania	LTP							
IFJ	Institute of Nuclear Physics	Research Institute	Poland	LTP			1				
JSI	Jožef Stefan Institute	Research Institute	Slovenia	BEN			1	1			
IMP	Nofer Institute of Occupational Medicine	Research Institute	Poland				1				
IMROH	Institute for Medical Research and Occupational Health	Research Institute	Croatia	BEN	1	1		1			
IN2P3	National Institute of Nuclear Physics and Particle Physics (IN2P3 - CNRS)	Research Institute	France			1					
INFN	IstitutoNazionale di FisicaNucleare	Research Institute	Italy		1		1				
IORH	SERBIAN INSTITUTE OF OCCUPATIONAL HEALTH	Research Institute	Serbia				1				
IOV	IstitutoOncologico Veneto	Research Institute	Italy	TP	1						
IPCESCOLA S	*IPC-Escola Superior de Tecnologia da Saúde de Coimbra*	University	Portugal						1		
IPH	Institute of public Health	National body	Macedonia				1				
IPOP	InstitutoPortugues de Oncologia do Porto	Research Institute	Portugal				1				
IR	Institute of Radiobiology of NAS of Belarus	Research Institute	Belarus					1			
IRA	University Institute for Radiation Physics	Research Institute	Switzerland		1		1				
IRSN	Institut de Radioprotection et de SuretéNucléaire	Research Institute	France	BEN	1	1	1	1	1	1	
IS CAS	Institute of Sociology of the Czech Academy of Sciences	Research Institute	Czech Republic							1	
IS Global	Institut de Salut Global	Research Institute	Spain	LTP	1			1		1	
ISS	InstitutoSuperiore di Sanita	Research Institute	Italy	BEN	1		1				
IST	Instituto Superior Técnico	Research Institute	Portugal	LTP	1	1	1	1			
IU School	IU School	Association	United States	TP							
JCU	University of South Bohemia	University	Czech Republic		1					1	

JRC-ISPRA	European Commission – Joint Research Centre	Research Institute	International					1		
Juelich	FORSCHUNGSZENTRUMJULICH GMBH	Research Institute	Germany	LTP						
JYU	University of Jyväskylä	University	Finland							1
KCOR	National Centre for Radiation Protection in Health Care	National body	Poland				1			
KIT	Karlsruhe Institute of Technology	Unversity	Germany	LTP	1		1	1		
KNMI	The Royal Netherlands Meteorological Institute	Research Institute	The Netherlands	TP						
KU	Kingston University, London	University	United Kingdom							1
KVSF	Network of Competence in Radiation Research ,	Association	Germany		1					
Landauer	Landauer	SME	France				1			
LARUEX	University of Extremadura: LARUEX	University	Spain			1				
LEGMC	Latvian Environment, Geology and Meteorology Centre (LEGMC)	National Body	Latvia				1			
LUH	Leibniz Universität Hannover	University	Germany			1				
MarkkuLehtonen	historian/nuclear governance	individual	Finland							1
MBS AC UK	Manchester business school	University	United Kingdom					1		
MED LU	Lund medical faculty of medicine	University	Sweden					1		
MedUni Vienna	MedUni Vienna - Medical University of Vienna, Austria	University	Austria	BEN	1					
MELODI	Association Melodi	Association	France	BEN						
MERIENCE	Promoting dialogue to inspire solutions for complex environmental & socio-technical challenges	SME	Spain							1
MET.no	Norwegian Met Institute	National body	Norway	TP						
MetOffice	MET OFFICE	National body	United Kingdom	LTP						
MINECO	MINECO-Minesterio De Economia y Competitividad	Funding Agency	Spain	BEN						
Mirion	Mirion Technologies - Dosimetry Services Division	SME	United States				1			
MP	Medical Physics, Lund university	University	Sweden				1			
MSKCC	Memorial Sloan Kettering Cancer Center	Research Institute	United States	TP						
MTA EK	Hungarian Academy of Sciences, Centre for Energy Research	Research Institute	Hungary	BEN	1		1	1		

MUTADIS	risk governance R&D team	SME	France	LTP				1		
Nadia Zeleznik	psychologist/nuclear physics/president Nuclear Transparency Watch	Individual	Slovenia					1		1
NCBJ	National Centre for Nuclear Research	Research Institute	Poland				1	1		
NCRRP	Ministry of Health, National Centre of Radiobiology and Radiation Protection ,	Research Institute	Bulgaria	BEN	1					
NCSRD	The National Center for Scientific Research "Demokritos" (NCSRD)	Research Institute	Greece	LTP		1		1		
NERIS	ASSOCIATION DE LA PLATEFORME EUROPEENNE NERIS	Association	France	BEN						
NIPH	Norwegian Institute of Public Health	Research Institute	Norway		1					
NIPNE	Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering	Research Institute	Romania					1		
NNCRK	National Nuclear Center of the Republic of Kazakhstan	Research Institute	Kazakhstan			1				
NPL	National Physical Laboratory	Research Institute	United Kingdom				1			
NRG	Nuclear Research and Consultancy Group	SME	The Netherlands			1	1			
NRI	UJVREZ, a. s.	University	Czech Republic	LTP						
NRIRR	Frédéric Joliot-Curie National Research Institute for Radiobiology and Radiohygiene	Research Institute	Hungary	BEN	1		1			
NTUA	NATIONAL TECHNICAL UNIVERSITY OF ATHENS - NTUA	University	Greece	LTP						
NU	Nagasaki University	University	Japan					1		
Nuvia	Nuvia Ltd	SME	United Kingdom				1			
OBU	OXFORD BROOKES UNIVERSITY	University	United Kingdom	LTP						
PAAGOV	national atomic energy agency	National body	Poland					1		
PDC-ARGOS	software system to support the emergency organization	SME	Denmark	LTP				1		
PHE	Public Health England-Department of health	Research Institute	United Kingdom	BEN	1		1	1		
PHI	Public Health Institute	Research Institute	Bosnia and Herzegovina				1			
PRI	Institute of Radiation Protection	Research Institute	Ukraine				1			

PSI	Paul Scherrer Institut	Research Institute	Switzerland				1			
PTB	Physikalisch-Technische Bundesanstalt	Research Institute	Germany	LTP			1			
RBI	Ruder Boskovic Institute	Research Institute	Croatia	LTP			1	1		
REC	REGIONAL ENVIRONMENTAL CENTER FOR CENTRAL AND EASTERN EUROPE -REC	Research Institute	The Netherlands	TP						
RIKILT	Institute of Food Safety	Research Institute	The Netherlands	TP						
RISOE	Risoe National Laboratory	Research Institute	Denmark				1			
RIVM	National Institute for Public Health and the Environment	Research Institute	The Netherlands	BEN	1			1		
RPII	Radiological Protection Institute of Ireland	Research Institute	Ireland				1			
RSC	Radiation Protection Centre	Research Institute	Lithuania	BEN			1			
RTU	RIGASTEHNISKAUNIVERSITATE	University	Latvia	LTP						
SCIENSANO	Institut Scientifique de Santé Publique,	Research Institute	Belgium		1					
SCK•CEN	Studiecentrum voor Kernenergie - Centre d'Etude de l'Energie Nucleaire	Research Institute	Belgium	BEN	1	1	1	1	1	1
SERGAS	Servizo Galego de Saúde	Research Institute	Spain		1					
SIS	National Institute of Radiation Hygiene	Research Institute	Denmark				1			
SL	Seibersdorf Laboratories	Research Institute	Austria	LTP			1			
SMHI	Swedish Meteorological and Hydrological Institute	Research Institute	Sweden					1		
SMU	Slovak Medical University	University	Slovak Republic				1			
SSM	Swedish Radiation Safety Authority	National body	Sweden	BEN	1	1	1	1		
St James's Hospital	St James's Hospital, Dublin	Hospital	Ireland	TP			1			
STUK	Radiation and Nuclear Safety Authority	Research Institute	Finland	BEN	1	1	1	1		1
SU	Stockholm University Centre for Radiation Protection Research	University	Sweden	LTP	1					
SUBI	Southern Urals Biophysics Institute (SUBI)	Research Institute	Russia	TP						
SURO	National Radiation Protection Institute	Research Institute	Czech Republic	BEN				1		
SYMLOG	Symlog	SME	France							1
TECNATOM	nuclear engineering company	SME	Spain				1	1		

THUNEN	Thünen Institute of Fisheries Ecology (THUNEN)	Research Institute	Germany			1				
TU Delft	Delft University of Technology	University	The Netherlands							1
TUDr	Technische Universitaet Dresden	University	Germany				1			
UA	University of Aveiro (UA)	University	Portugal			1				
UAB	Universitat Autònoma de Barcelona	University	Spain	TP	1					
UAM	Madrid Autonomous University,	University	Spain		1					
UB	University of Barcelona (UB)	University	Spain			1				
UCEWP	Ukrainian Centre of Environmental and Water Projects	National body	Ukraine					1		
Ucrete	University of Crete	University	Greece						1	
UEF	University of Eastern Finland	University	Finland	BEN	1					
UFC	Université Franche-Comté (UFC)	University	France	TP						
UGR	University of Granada (UGR)	University	Spain			1				
UHasselt	Hasselt University	University	Belgium							1
UHCZ	University Hospital Centre Zagreb	University	Croatia				1			
UHL	University Hospital Limerick	University	Ireland	TP						
UJF	Nuclear Physics Institute ASCR	Research Institute	Czech Republic	LTP			1			
UK	University of Kragujevac	University	Serbia				1			
UL	UL - LatvijasUniversitate, Latvia	University	Latvia	BEN						
UL	Lund University (UL)	University	Sweden	TP						
ULg	UNIVERSITE DE LIEGE	University	Belgium	LTP						
ULISBOA	Universidade de Lisboa	University	Portugal		1					
UMB	Matej Bel University	University	Slovak Republic							1
UNEX	University of Extramadura	University	Spain	TP				1		
unibremen	Bremen University	University	Germany					1		
UNIMI	University of Milano	University	Italy	LTP				1		1
UNINA2	Second University of Naples (SUN)	University	Italy		1					
Unipa	Universita di Palermo	University	Italy				1			
UniPavia	Uni Pavia - University PAVIA, Italy	University	Italy	BEN	1					
UnivDublin	University College Dublin	University	Ireland						1	
University of Exeter	University of Exeter	University	United Kingdom							1

University of Valencia	University of Valencia	University	Spain					1		
Univmainz	Medical university Centre Mainz	University	Germany						1	
UOA	University of Antwerp	University	Belgium							1
UOWM	Universtity of Western Macedonia	University	Greece					1		
UP	University of Porto (UP)	University	Portugal			1				
UPC	Universitat Politècnica de Catalunya	University	Spain	LTP			1			
UPM	Universidad Politécnica de Madrid	University	Spain				1	1		
UPV	University of the Basque Country (UPV/EHU)	University	Spain			1				
UROS	Universitaet Rostock	University	Germany		1					
URV	Rovira I Virgili University, Laboratory of Toxicology and Environmental Health	University	Spain		1					
USP	Universitadegli Studi di Pisa	University	Italy				1			
UT	UT - University of Tartu, Estonia	University	Estonia	BEN						
UTA	TAMPEREENKORKEAKOUL USAATIO SR	University	Finland	LTP						
UU	Uppsala University	University	Sweden				1			
UZH	University of Zurich	University	Switzerla nd	TP						
VIN	Institute of Nuclear Sciences - Vinca	Research Institute	Serbia	TP			1			
VUJE	nuclear power engineering company	SME	Slovak Republic	BEN				1		
WarwickUni	THE UNIVERSITY OF WARWICK	University	United Kingdom	LTP				1		
Wiv-ISP	Belgian Scientific Institute of Public Health	Research Institute	Belgium	TP						

7.2. Annex 2: Strategic Research Agendas of the Radiation Protection Research Platforms