GAP ANALYSES from EURADOS

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INTRODUCTION

EURADOS e. V. is registered in the German Register of Societies as a non-profit association for promoting research and development and European cooperation in the field of the dosimetry of ionizing radiation. Since autumn 2012, the European Radiation Dosimetry Group (EURADOS) has been developing its Strategic Research Agenda (SRA), which is intended to contribute to the identification of future research needs in radiation dosimetry in Europe. The present article summarises—based on input from EURADOS Working Groups (WGs) and Voting Members—five visions in dosimetry and defines key issues in dosimetry research that are considered important for the next decades. The five visions include scientific developments required towards (a) updated fundamental dose concepts and quantities, (b) improved radiation risk estimates deduced from epidemiological cohorts, (c) efficient dose assessment for radiological emergencies, (d) integrated personalised dosimetry in medical applications and (e) improved radiation protection of workers and the public. A detailed version of the SRA can be downloaded as a EURADOS report from the EURADOS website (www.eurados.org).

EURATOM has recently published a new call for Radiation Protection research, NFRP8, with a deadline of September 27th 2018. The call text specifically asks for a gap analyses to be performed in line with the prioritisation o of research in this field reflected in the strategic research agendas of the Radiation Protection Research Platforms:

"This action should seek close cooperation with and complement actions of CONCERT and MEDIRAD projects, strictly avoiding duplication. It aims at pursuing the integrative approach of radiation protection research (of radiation biology, radiation epidemiology, radioecology, medical applications, dosimetry, low-dose risk, emergency preparedness and response, etc.). It should complement the actions undertaken in response to the two above mentioned projects by providing incremental knowledge on the effects of ionising radiation on living beings, dosimetry and management of radiological and nuclear emergency. This action must take into account prioritisation of research in this field reflected in the strategic research agendas of the Radiation Protection Research Platforms. The pertinence and quality of the gap analysis will be considered during evaluation. It is recommended that this work should be undertaken using the working procedures established by the above-mentioned platforms. "

In this framework, EURADOS has performed a gap analyses, comparing the outcome of recently funded projects with the challenges identified in the EURADOS SRA. For this exercise, a list of recent European projects has been made. Only projects that are on-going or were finished after 2013 were included, because the SRA took into account results from older projects. Mainly FP7 funded projects from EURATOM were listed, including OPERRA and CONCERT projects. Also some SECURITY projects were considered. Some EURAMET projects have clear links with the EURADOS priorities and were considered as well, although the focuss was much more on metrological aspects than on radiation protection research.

There was only limited time to perform this gap analyses, and the evaluation of how much a certain project had contributed to the EURADOS challenges was done by members of the EURADOS Council and the Workin Group chairs. Because of this limited time, it was not possible to contact the coordinators of the concerned projects.

VISION 1: TOWARDS UPDATED FUNDAMENTAL DOSE CONCEPTS AND QUANTITIES

The current radiation protection system is based on operational quantities recommended by ICRU and protection quantities recommended by ICRP. Both are derived from absorbed dose using weighting factors to take into account tissue sensitivity and radiation quality on the biological outcome. For radiation quality, defined by particle type and energy spectrum, the weighting factors are too simplistic because the actual biological effectiveness is related to particle track structure, the

stochastic pattern of energy depositions, which has a complex relationship to the energy/type of radiation incident on the body/phantom. A novel concept of radiation quality based on measurable properties of this particle track structure, such as microscopic distributions of energy deposition or ionisations, and its experimental realisation with 'dosemeter standards', would allow alternative quantities based on nano- and microdosimetry to be developed for predicting health effects instead of absorbed dose averaged over an organ or tissue.

- **Challenge 1: To improve understanding of spatial correlations of radiation interaction events (priority 12)**

Detailed numerical simulations of track structures have provided evidence that the dependence of biological effectiveness on radiation quality of early occurring DNA strand breaks is strongly related to target sizes in the range of few nanometres. Trackstructure characteristics for other target sizes may be relevant for later biological end points such as chromosomal aberrations or cell death. Hence, techniques for track-structure characterisation, simulating a range of target sizes on the nanometre scale, need to be developed, and the link between nano- and macrodosimetry must be studied. Experimental investigation of radiation interactions with real nanometric objects in the condensed phase and establishment of uncertainty budgets for measured nanodosimetric quantities are further important tasks. The results of these efforts will provide a benchmark for the validation of simulation codes. Improved track-structure codes must be developed that overcome the issue of Monte Carlo techniques using classical trajectories and the cross-section concept not being appropriate at the nanometre scale.

GAP ANALYSES:

This topic was not covered at all in any of the previous FP7 projects

- **Challenge 2: To quantify correlations between track structure and radiation damage (priority 1)**

The correlation between track structure and radiation damage must be established in a quantitative way. For this, cells need to be exposed to single particle tracks keeping the geometrical relation between the particle track and the exposed cell. In these experiments, the required radiobiological assays must be improved in terms of statistical power, useable cell types, etc. The physical characteristics of the track structures involved should be explored by using nanodosemeters with multi-scale measurement capabilities or by employing track-structure simulation codes that have been benchmarked using nanodosimetric measurements. Statistical cross analysis should then identify correlations between the yield of a particular biological end point and nanodosimetric quantities characterising the particle tracks. A variety of human cell types of different differentiation and coming from donors of different age and sex should be investigated.

GAP ANALYSES:

This topic was not covered in any of the previous FP7 projects. There was an EMRP (EURAMET) project BIOQUART (Biologically Weighted Quantities for Radiotherapy). The aim of BioQuaRT was to develop measurement and simulation techniques for determining the physical properties of ionising particle track structure on different length scales, and to investigate at the cellular level how these track structure characteristics correlate with the biological effects of radiation. It made some progress in this field, but still a lot of work is needed to come to a better understanding of the correlations between the track structure and radiation damage.

- **Challenge 3: To improve understanding of biokinetics of internal emitters (priority 11)**

Low concentrations of incorporated radionuclides such as alpha and beta emitters are characterised by spatially and temporally inhomogeneous dose distributions within a tissue or organ, e.g. plutonium and strontium isotopes in the skeleton, short-lived radon and thoron progenies in regions of the respiratory tract and Auger emitters such as some radioiodine isotopes in the thyroid. For example, alpha emitters may induce high doses on a local scale that may lead to cell killing, although the mean absorbed lung dose might be low. Hence, characterisation of the spatial inhomogeneity of dose and its effects from individual molecules to the whole body is needed, including benchmarking of track-structure Monte Carlo codes. These efforts must be accompanied by the development of more realistic models of radionuclide deposition in the relevant organs and by describing their energy deposition on a micrometer and nanometer scale to estimate the corresponding local biological effects. The results should be combined with available epidemiological observations. Tissue response may be different from that observed in individual cells, e.g. through bystander mechanisms. This raises the question of whether progenitor cells or also surrounding cells are the primary radiation target. Moreover, it is common practice to assume that cancer initiation is related to cellular transformation in single cells and thus depends on the local dose, while an important promotional factor is inflammation of the irradiated tissue, which is again related to local dose. This again raises the question of which cells in a tissue are the primary targets for initiation and promotion and, consequently, which are the relevant cellular doses.

GAP ANALYSES:

This topic was not covered in most of the previous FP7 projects. The CURE project was dedicated on Uranium exposure for epidemiology. It sought to develop a new study based on modern biological approaches, joint analysis of the main

cohorts of workers monitored for uranium exposure, and the latest internal dose calculation models. This three-pronged approach aimed to improve the potential for characterizing the biological and health effects of chronic exposure to low doses of uranium. Also the SOLO project did some work on internal dosimetry for plutonium in the framework of an epidemiology study.

- **Challenge 4: To update operational quantities for external exposure (priority 10)**

Operational quantities should provide a reasonable estimate of the protection quantities, for optimisation and in assessing compliance with the limits. Conversion coefficients for both types of quantities have been published by ICRU and ICRP for photons, neutrons and electrons. ICRP has recently published revised protection quantities in standard male and female adult anthropomorphic phantoms and conversion coefficients for the updated protection quantities including an extension in particle type and energy range. The operational quantities provide a reasonable approximation to the new protection quantities, but with a number of limitations, including the absence of values of conversion coefficients for new particles and for extended energy ranges. Additionally, consideration is needed of operational quantities for the assessment of local skin dose and lens of the eye dose. Further development is required on devices and calibration facilities, as well as the establishment of calibration procedures, to determine the operational quantities. Progress in nanodosimetry may demonstrate the need for revised protection and operational quantities that better reflect the radiation damage in the body.

GAP ANALYSES:

This topic was not covered in most of the previous FP7 projects. However, since our SRA was written, ICRU has proposed a new approach for the operational quantities. So part of this challenge is addressed, creating of course new actions to investigate the consequences of these proposed changes.

VISION 2: TOWARDS IMPROVED RADIATION RISK ESTIMATES DEDUCED FROM EPIDEMIOLOGICAL COHORTS

Current knowledge of relationships between dose and cancer and non-cancer diseases, and other radioinduced pathologies (e.g. eye lens opacity, fibrosis), depends largely on the analysis of situations where large populations have been exposed either acutely or chronically to ionising radiation. Among occupationally exposed groups, uranium miners, Chernobyl liquidators, Mayak workers, other nuclear workers, air crew, medical staff, etc. are of concern, while other studies include individuals exposed as a consequence of radiotherapy. Cohorts that may become more and more important in the future may include offspring cohorts of exposed parents. Cohorts such as radiotherapy patient populations, for example, are also useful because of the large number of individuals involved, the medium–high doses, and because accurate patient doses can be obtained. Large populations can also be obtained from diagnostic imaging patients. Other efforts include the establishment of national cohorts of individuals of the general populations who may benefit from dosimetric information and the setup of biobanks for physical and biological analyses.

- **Challenge 1: To explore exposure pathways not yet considered or validated (priority 13) and**
- **Challenge 2: To improve retrospective dosimetry for exposure pathways already considered (priority 14)**

It is important to note that whatever the cohort under consideration, development and harmonisation of dosimetry are essential. This is so because the basis for all risk estimates deduced from these cohorts is—among others—the dose. In order to give maximum support for current and future epidemiological and molecular epidemiological studies and to underpin theoretical radiobiological developments, dose distributions in the body following exposures from all known sources of radiation should be quantified and evaluated, in particular for mixed radiation fields that were present, for example, at work places of nuclear workers, or if there were multiple exposures to ionising radiation in medical applications (diagnostics and therapy). Moreover, to reduce bias in retrospective (bio) dosimetry, confounding factors such as chemical or biological contaminants or stressors should be identified and reduced and the age and sex dependence of radiation effects studied. In the past, in most cases, incidence and/or mortality of various cancer types were of major concern, while more recently, cancer diseases following in-utero exposure and non-cancer diseases such as cardiovascular diseases, neurological impairments or eye lens opacities have become of increasing concern. This raises new challenges, and a number of dosimetric improvements are required that include:

(a) Quantification and validation of exposure pathways that have not yet been considered thus far for certain cohorts. This includes doses to certain organs and tissues that need specific attention (e.g. eye lens, blood, brain, foetus), doses to

substructures of certain organs (e.g. heart arteries and walls) and determination of the micro-distribution of doses in certain tissues (e.g. in the respiratory tract after inhalation of alpha emitters);

(b) Improvements in techniques of retrospective dosimetry for historical cohorts and validation of the estimated doses (e.g. for Chernobyl liquidators, Techa River populations, atomic bomb survivors, Mayak and Sellafield nuclear workers, uranium miners), which may also include quantification of additional exposures such as those due to residual radiation among the atomic bomb survivors and due to solar particle events among air crew;

(c) Improvement of uncertainty evaluation of doses estimated by retrospective dosimetry techniques.

GAP ANALYSES:

Several EC project have included epidemiological studies, which included a dosimetric studies. Some of these projects have developed further or improved the dosimetry techniques and have reduced the uncertainties, and can as such be considered as contributing to this challenge.

SOLO pooled the Sellafield worker, Mayak andTecha River cohorts to assess risks from exposures in utero and from plutonium in workers. CURE did similar things for Uranium workers, INWORKS forgeneral nuclear industry workers, while COCHER looked at Chernobyl survivors.

The EURALOC project improved the dosimetry for the eye lens with interventional cardiologists.

Several projects used also patient data in their studies, and have contributed to better dose determination at organ level for patient treatments. EPI-CT looked at CT exposure with children. PROCARDIO and CEREBRAD looked at childhood cancer survivors (heart and brain doses respectively). Also MEDIRAD will improve the organ dosimetry of patients undergoing different medical procedures. And ANDANTE improved the dosimetry of peripheral organs during radiotherapy, including neutron doses.

It will stay important to include a major dosimetric workpackage in each project that deals with epidemiology. And the uncertainties on the retrospective dosimetry remain large in all cases (workers, internal doses, patient doses) so that continuous effort is needed to reduce these uncertainties.

VISION 3: TOWARDS AN EFFICIENT DOSE ASSESSMENT IN CASE OF RADIOLOGICAL EMERGENCIES

Radiological emergencies are considered a major challenge of modern societies, including incidents that have an impact on large geographical areas and lead to exposure of large groups of the general population, terroristic attacks and accidents that involve industrial or medical radiation sources. Each of these exposure scenarios is associated with specific problems in determining the radiation doses, identifying individuals who are at the highest risk and deciding the best method to be applied for evacuation, medical treatment and remediation. The needs in terms of dosimetric protocols and techniques depend in particular on the number of victims and the severity of the exposure: at the first stage, triage is of importance, while at the second stage, more precise dose investigations are needed on identified victims.

- **Challenge 1: To identify and and characterize new markers of exposure (priority 8)**

A quick, efficient and reliable estimate of doses to affected individuals is required before any further decisions can be made by the responsible authorities. Moreover, real-time monitoring data might be scarceand rapidly change with time. A number of dosimetric improvements are therefore considered important to enable decision makers to initiate the most urgent actions. For example, rapid identification of individuals with high risk of developing radiationinduced injuries, among hundreds or even thousands of ‘worried-well’, is essential. Further efforts are needed towards identification of materials of daily life that could be used as fortuitous dosemeters, measureable by electron paramagnetic resonance (EPR), thermoluminescence (TL) and optically stimulated thermoluminescence (OSL). These techniques can also be applied to biological materials such as tooth enamel, finger nails and hairs, preferably by mobile systems for application in the field, which need to be developed. Other objects that were exposed at a certain place could also be used. For the computational techniques applied, automatic direct input of dose rate measurement data into databases, interpolation and extrapolation algorithms and tools for prediction of doses are the main routes of further development of efficient techniques.

- **Challenge 2: To develop strategies and methods to increase measurement capacity (priority 16)**

In order to handle a large number of dosimetric samples, strategies and methods to increase measurement capacity must be developed. One solution is automation of sample preparation and measurement, in particular for analysis of dicentric

chromosomes and micronuclei where the evaluation of metaphases should be fully automated. Additionally, methods for high-throughput and cheap measurements should be further developed such as gene expression or protein biomarkers. Web-based scoring of captured images is emerging as a fast and easy method of performing chromosome analysis whilst involving laboratories spread all over the world, and networking of laboratories has been identified as a very useful approach to get fast and reliable dose estimates. Such networks have been or are in the process of being established, but they need to be maintained and their functionality has to be trained and practised.

GAP ANALYSES:

This challenge was an important topic in 2 recent projects. RENEB established a European network in biological dosimetry that will guarantee highest efficiency in processing and scoring of biological samples for fast, reliable results implemented in the EU emergency management. MULTIBIODOSE was a security project that analysed a variety of biodosimetric tools and adapted them to different mass casualty scenarios.

In the recently started CONCERT project CONFIDENCE the uncertainty of radiological data will be investigated and its further propagation in decision support systems and dose estimation in case of accidents. This is also related to this challenge.

Increasing the measurement capability was also an important topic in the 2 recent projects RENEB and MULTIBIODOSE. CATHYMARA adressed the specific topic of thyroid measurements.

Next to these, also other projects adressed and are adressing this important issue indirectly, like SHAMISEN and TERRITORIES, by analysing past experiences and making recommendations. This will be continued in the new CONCERT project SHAMISEN SINGS.

Despites these recent projects, there remains still research to be done for better and faster etimation of doses in case of emergencies, using different physical and biological techniques. The dosimetry in emergencies is still far from ideal.

- **Challenge 3: To quantify doses after accidental internal contamination (priority 3)**

For dose assessment after internal contamination, efforts should be made to link internal dosimetry from incorporated radionuclides with biological dosimetry methods. This would require definition of suitable biological end points, definition of the proper dosimetric quantity to be compared with the biological end point (e.g. blood dose instead of administered activity) and identification of cases for which sufficient biological dosimetry and bioassay data are available to be used for method validation. These studies could also be performed using radiopharmaceuticals. Specific emergency bioassay methods for in vitro monitoring of radionuclides, such as transuranic isotopes, must be either improved or developed, and then validated. For other radionuclides such as radioiodine isotopes, new thyroid phantoms of various sizes should be developed for in vivo monitoring and computational dosimetry. These actions should be complemented by development of counter measures to reduce doses after accidental internal contamination. In particular, for transuranic isotopes, reference biokinetic models under diethylene triamine pentaacetic acid therapy should be developed to improve the reliability of dose assessments in such cases.

GAP ANALYSES:

The first CONCERT call project CONFIDENCE will handle partial aspects of accidental internal contamination, as did SHAMISEN. CATHYMARA adressed the specific topic of thyroid measurements.

Still, there is a lot of work to improve the real dose determination after accidental internal contamination for a whole series of isotopes.

VISION 4: TOWARDS AN INTEGRATED PERSONALIZED DOSIMETRY IN MEDICAL APPLICATION

Modern medicine offers a variety of diagnostic and therapeutic procedures that involve ionising radiation, and consequently medical exposures are largely responsible for exposure from man-made sources of ionising radiation. In European countries, a considerable fraction of the population is being treated by radiotherapy. The distribution of dose within the body following radiotherapy, in particular in healthy tissues outside the tumor, varies considerably with many factors, and doses can vary spatially from tens of gray to milligray. All parts of the dose–risk curve for subsequent cancer induction are therefore involved, from the region where low-dose effects occur, through the region defined largely by the atomic bomb survivors, to the further non-linear region at high doses where cell kill and re-population effects are known to occur.

- **Challenge 1: To establish out-of-field dosimetry for photon and particle therapy (priority 5)**

Epidemiological studies of second cancers following radiotherapy require specification of dose to the patient at the site of the subsequent malignancy, making outof- field dosimetry for photon and particle therapy an important field of dosimetric development, including the development of analytical models for outof-field dosimetry calculations.Moreover, becauseadditional dose contributions may come from diagnostic procedures, epidemiological studies will require quantification of all sources (therapy and/or imaging) for an estimation of combined risk, which must be harmonised and combined. This could be done by means of computational methods supported by the development of novel small-scale detectors for neutrons and photons that could be used to measure the dose distribution within dedicated phantoms irradiated according to typical radiotherapy treatments and modalities. Special attention must be given to paediatric radiotherapy and hadron radiotherapy where high-energy secondary neutrons are produced. As an ultimate goal of this research, calculation of a complete map of doses for each individual patient would be possible.

GAP ANALYSES:

ANDANTE focussed on the neutron exposure in the out-of-field organs. Other projects like PROCARDIO and CEREBRAD looked at secundary effects after radiotherapy for specific organs, and have done some dosimetric work for this. In MEDIRAD work will be done on cardiovascular effects after breast radiotherapy, including an epidemiological study.

Still, a generic study of out-of-field dosimetry, combined with imaging doses, have not been adressed in any project.

- **Challenge 2: To improve dosimetry in modern external beam radiotherapy (priority 6)**

The rapid development in new radiotherapy techniques requires a continuous effort in dosimetry research, not only for out-of-field doses. There is also a need to develop experimental online dosimetry techniques and to improve calibration techniques. Indeed, it is important to be able to check whether the planned dose distribution to the tumour region is accurately administered.

GAP ANALYSES:

This topic was not covered at all in any of the previous FP7 projects. There were some EMPIR and EMRP projects focussing on metrological aspects, like MRgRT (metrology for MR guided radiotherapy), Absorb (Absorbed dose in water and air) and MetrExtRT (metrology for radiotherapy using complex radiation fields).

- **Challenge 3: To improve internal microdosimetry in radiotherapy and medical imaging (priority 15)**

Radiopharmaceuticals have been used in medical imaging and radiotherapy, respectively, to diagnose and to treat cancer and other diseases. The features of cellular and molecular radiobiological effects involved depend strongly on the spatial and temporal distributions of initial physical tracks, on induced chemical radicals and later on dynamical molecular progresses. The analysis should cover alpha and Auger emitters and beta radiation at the levels of molecule, cell, tissue, organ and organism. Furthermore, the potential application of gold or other nanoparticles in medical diagnostic imaging and radiotherapy should be investigated. Molecular biological experimental and theoretical Monte Carlo simulation studies on a micro- and nanometre scale are considered important to reveal the correlation between the experimental biological findings at the cellular level in specific organs, like the lungs and kidneys, and the micrometer and nanometer scale doses of these emitters.

GAP ANALYSES:

This topic was not covered at all in any of the previous FP7 projects

- **Challenge 4: To optimize dose and risk estimations in interventional radiology (priority 7)**

Operational quantities should provide a reasonable estimate of the protection quantities, for optimisation and in In interventional radiology, medical dosimetry is important because the dose to patients can be high, leading even to tissue reactions that may be increased when using low-energy photons below few hundred keV. Thus, an improved system of dose calculation and dose monitoring for adult and paediatric patients needs to be developed (including skin dose measurements, calibration procedures for dose measuring devices, organisation of intercomparisons between clinics and development of online patient dosimetry procedures). This would enable assessment and improved use of diagnostic reference levels (DRLs) and other quantities for optimisation of patient doses, and improved accuracy of skin and other organ doses. The final goal would be patient-specific real-time dose mapping of various dose quantities with known uncertainty and with efficient use of digital imaging and communications in medicine (DICOM) information. Thus, practical systems of patient dose monitoring for local as well as wide-scale evaluation and comparison of patient doses will be available. These systems can be used to estimate and optimise patient doses and radiation- induced risks and to prevent accidents.

GAP ANALYSES:

Two on-going projects cover some parts of this challenge. VERIDIC will focuss on skin doses during interventional procedures. MEDIRAD will look at organ doses during such interventional procedures, and will work on facilitating the retrieval of dose information from the DICOM header.

- **Challenge 5: Establish reliable patient dosimetry in CT examinations (priority 9)**

As for computed tomography (CT) examinations, establishment of reliable patient dosimetry is also important. This could be done by developing automatic systems of dose monitoring (with known uncertainties) and scanner calibration using dedicated phantoms in order to provide easy use of DRLs, improved optimisation of patient doses and improved accuracy of organ doses for risk estimation and population dose estimation. In an effort towards personalised dosimetry, methods of patient dose determination should cope with varying patient sizes. The focus should be on paediatric patients, and dose optimisationmust be considered as key feature of these efforts, especially in view of the rapid development of new CT techniques

GAP ANALYSES:

Similar as for interventional procedures, MEDIRAD will also look at CT examinations. For pediatric examinations, EPI-CT did a lot of work for dose estimations. DIMITRA did the same for dental cone beam CT, while BREAST-CT looked at breast CT exposures.

VISION 5: TOWARDS AN IMPROVED RADIATION PROTECTION OF WORKERS AND THE PUBLIC

- **Challenge 1: To refine, validate and implement new biokinetic models (priority 18)**

The assessment of dose from internal exposure to radionuclides is subject to uncertainty due to activity measurement errors, individual variability, imperfection of biokinetic and dosimetric models and unknown parameters of exposure. Work required will include implementation of the latest biokinetic models including age- and sex-dependent biokinetic parameters. Dose assessment due to administration of (short-lived) radiopharmaceuticals to patients should consider the influence of certain diseases on biokinetic parameters adapted to the short half-lives of the isotopes considered, and the realistic modelling of blood retention and urinary bladder voiding. This is needed to allow modification of standard biokinetic models that were developed for longer-lived radionuclides, based on data from healthy persons. In this context, the availability of databases including autopsy cases should be used to validate any new biokinetic model. The results of these developments should be transferred to operational radiation protection, including guidelines and technical recommendations.

GAP ANALYSES:

This topic was not covered at all in any of the previous FP7 projects.

- **Challenge 2: To develop calibration procedures for partial body counters**

In vivo measurements using partial body counters represent a valuable method in internal dosimetry, providing actual information on radionuclide activity within the body of an individual. However, there is no standard calibration procedure, and suitable anthropomorphic phantoms to assess, for example, the skeletal activity of bone-seeking radionuclides are scarce.To reduce the uncertainties in in vivo measurements, the influence of individual body parameters and phantom characteristics on the detection efficiency must be investigated. Phantom development should include construction of new physical phantoms complemented by their mathematical representation in order to account for individual variability of the persons to be measured.

GAP ANALYSES:

Partial body counters were only adressed in the CATHYMARA project, but this was limited to thyroid monitoring.

- **Challenge 3: To develop accurate and on-line personal dosimetry for workers (priority 4)**

A further challenge is to provide online personal dosimetry for occupationally exposed workers. This requires monitoring of workers in real time for all limiting quantities (including whole body, eye lens, extremities, brain and heart doses). Well-characterised active personal and area dosemeters should be developed for all relevant dosimetric quantities including all relevant radiation fields, especially pulsed fields, with and without shielding, as well as computational tools using advanced tracking technology. Further consideration is needed taking into account their potential for use as official dose record. The inclusion of dosimetry of other potentially radiosensitive organs (brain, heart) might also be needed depending on the outcome of biological research on the brain and cardiovascular risk.

GAP ANALYSES:

For on-line dosimetry, a new CONCERT project PODIUM was approved and started in 2018. Dosimetry of other radiosensitive organs (like heart and brain) for radiation workers is not yet adressed fully in any project. Active dosemeters are still missing for many applications.

- **Challenge 4: To develop neutron dosimetry techniques further (priority 2)**

Neutrons are intentionally used or incidentally created in various scientific and technical applications, and they can dominate the total dose received. Neutron dosimetry is still challenging as neutrons are present in mixed fields and are indirectly ionising particles. Their energy range may cover up to 12 orders of magnitude, they show a wide range of angles of incidence and their conversion coefficients from fluence to dose vary by a factor of 50 over the entire energy range. Some neutron fields represent new challenges, for example, due to strongly pulsed radiation and/or high energy ranges, and proper reference fields are needed. The characterisation of workplace fields is complex and requires sophisticated procedures. Better and easier-to-use methods are needed, allowing the uncertainty of results to be evaluated. The detection threshold of neutron personal dosemeters and their energy and angular dependence remain the main deficiencies of neutron personal dosimetry compared with that for photons.

GAP ANALYSES:

Neutron dosimetry was not covered in recent projects. Only the ANDANTE projects covered the biological aspects of neutrons in the frame of peripheral doses in radiotherapy.

Neutron exposure of radiological workers will be partially covered by the newly started PODIUM project, where computational tools will be used to estimate neutron exposure.

The improvement of neutron dosimetric measurement techniques were not covered in any projects.

- **Challenge 5: To include nuclide-specific information in environmental monitoring (priority 17)**

As for radiation protection of members of the public, permanent and reliable environmental radiation monitoring is indispensable, and nuclide-specific information and data on ground and air contamination levels are of key importance for adequate governmental decisions. Therefore, novel and improved instrumentation for field station use should be developed to allow for measurement of dose rates and collection of nuclide-specific information. New and improved measurement systems based on ‘high-resolution’ spectrometric detectors require comprehensive scientific investigations of detector features, spectra evaluation and de-convolution methods. These systems could become the core instrumentation of the next generation of environmental radiation monitoring networks in Europe.

GAP ANALYSES:

This challenge will be partially important in the recently started CONCERT project CONFIDENCE, which deals with radiological uncertainties in decision making.

Two recent EURAMET (EMPIR) projects were focussed on the metrological aspects of this challenge: PREPAREDNESS and METROEMR.

Despites these recent projects, there remains still research to be done for improving monitoring including lay people, drones and European wide harmonisation of tools and methods.

CONCLUSION

Following lists gives an overview of the status of the different challenges relative to the EC funded projects of the last years. Included between brackets is the priority of these challenges. These priorities were determined by the EURADOS community, and reflect how important the EURADOS members find these challenges.

It is clear that none of the challenges is completely covered by past projects. There is need for many research projects in the different vision to make further significant progress in dosimetry for radiation protection. Still, because the amount of money is limited in the next EURATOM NFRP8 call, we decided to put forward only the challenges in group A as priorities for this call. For simplification and because they are linked, challenges 1.1 and 1.2 will be combined, as well as 1.3 and 5.1.

A. Challenges not or hardly covered

- **Challenge 1.2: To quantify correlations between track structure and radiation damage (priority 1)**
- **Challenge 5.4: To develop neutron dosimetry techniques further (priority 2)**
- **Challenge 4.2: To improve dosimetry in modern external beam radiotherapy (priority 6)**
- **Challenge 1.3: To improve understanding of biokinetics of internal emitters (priority 11)**
- **Challenge 1.1: To improve understanding of spatial correlations of radiation interaction events (priority 12)**
- **Challenge 4.3: To improve internal microdosimetry in radiotherapy and medical imaging (priority 15)**
- **Challenge 5.1: To refine, validate and implement new biokinetic models (priority 18)**

B. Challenges partially adressed

- **Challenge 3.3: To quantify doses after accidental internal contamination (priority 3)**
- **Challenge 4.1: To establish out-of-field dosimetry for photon and particle therapy (priority 5)**
- **Challenge 1.4: To update operational quantities for external exposure (priority 10)**
- **Challenge 5.2: To develop calibration procedures for partial body counters**

C. Challenges extensively covered

- **Challenge 5.3: To develop accurate and on-line personal dosimetry for workers (priority 4)**
- **Challenge 4.4: To optimize dose and risk estimations in interventional radiology (priority 7)**
- **Challenge 3.1: To identify and and characterize new markers of exposure (priority 8)**
- **Challenge 4.5: Establish reliable patient dosimetry in CT examinations (priority 9)**
- **Challenge 2.1: To explore exposure pathways not yet considered or validated (priority 13)**
- **Challenge 2.2: To improve retrospective dosimetry for exposure pathways already considered (priority 14)**
- **Challenge 3.2: To develop strategies and methods to increase measurement capacity (priority 16)**
- **Challenge 5.5: To include nuclide-specific information in environmental monitoring (priority 17)**