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EURADOS STRATEGIC RESEARCH AGENDA: VISION FOR DOSIMETRY OF IONISING RADIATION

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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. The SRA of EURADOS will be used as a guideline for future activities of the EURADOS WGs. A detailed version of the SRA can be downloaded as a EURADOS report from the EURADOS website (www.eurados.org).

INTRODUCTION

The European Radiation Dosimetry Group (EURADOS) was founded in 1981. It comprises a self-sustainable network of about 60 European institutions such as research centres, university institutes, reference laboratories, dosimetry services and companies, including about 500 scientists active in the field of radiation dosimetry. The aim of the network is to promote European cooperation in research and development in the dosimetry of ionising radiation and its implementation in routine practice in order to contribute to compatibility within Europe and conformance with international practices. For this, EURADOS has established working groups (WGs) on various dosimetric disciplines such as harmonisation of individual monitoring, environmental dosimetry, computational dosimetry, internal dosimetry, dosimetry for medical applications, retrospective dosimetry and dosimetry in high-energy radiation fields. These WGs demonstrate EURADOS' capacity to develop, test and compare novel dosimetric techniques and, consequently, reduce uncertainty in dosimetry. This expertise is also considered important for tackling problems arising from new applications of ionising radiation needed to contribute to science-based policy recommendations in this area. Harmonisation and education and training are also important activities for EURADOS, through the organisation of intercomparisons (e.g. intercomparisons on individual and environmental monitoring, dose assessment in the case of internal exposure, computational methods in dosimetry)[1–4] and training courses. More details on EURADOS may be found on the EURADOS website (www.eurados.org).

Since autumn 2012, the EURADOS WGs have collected proposals for topics related to dosimetry, which are believed to be important to the future of radiation research. During the EURADOS Annual Meeting that was held in February 2013 in Barcelona, Spain,

EURADOS Council established a Strategic Research Agenda (SRA) Editorial Group who put together all collected information and began to draft the SRA. The developed document was discussed in detail at various levels (WGs, Council, Voting Members) and was presented at various occasions. Thereafter, the document was finalised and published as the EURADOS SRA (first version) on the EURADOS website (www.eurados.org). This version will be the basis for a second round of improvements including stakeholder input from outside the dosimetric community in the future.

The identified topics are expected, if critically addressed over the coming decades, to significantly advance dosimetry in various applications. The EURADOS SRA is intended to provide input for the recently launched Open Project for European Radiation Research Area (OPERRA) funded by the European Commission (EC) that aims to build up a coordination structure that has the legal and logistical capacity to administer future calls for research proposals in radiation protection on behalf of the EC. Other projects such as the recent European Joint Programme Co-fund Action (EJP) intended to implement activities to attain objectives common to Horizon 2020 may also benefit from this SRA.

It is noted that the efforts of EURADOS to develop an SRA for dosimetry complement the efforts of other European platforms such as MELODI, ALLIANCE and NERIS, which are developing their own SRA in the fields of low-dose research, radioecology and emergency preparedness, respectively. Taken together, these SRAs will allow identification of research needs in Europe, in the general scientific field of radiation research, with the final goal of improving radiation protection of workers and the public.

The present article formulates—based on input from EURADOS WGs and Voting Members—five visions in dosimetry. The five visions include scientific developments 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.

Although the present article is based mainly on contributions from EURADOS members, it does include some indirect input from other institutions such as the International Commission on Radiological Protection (ICRP), the International Commission on Radiation Units and Measurements (ICRU), the International Organization for Standardization (ISO) and associations from the medical field, because a number of EURADOS members are also members in these institutions. A more formal process of involvement of stakeholders from outside the dosimetric community will be initiated at a later stage of SRA development.

VISION 1: TOWARDS UPDATED FUNDAMENTAL DOSE CONCEPTS AND QUANTITIES

The current radiation protection system is based on operational quantities recommended by ICRU[5] and protection quantities recommended by ICRP[6, 7]. 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[8, 9]. 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.

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[10]. Track-structure 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.

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[11] 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.

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[12–14], short-lived radon and thoron progenies in regions of the respiratory tract[15–17] and Auger emitters such as some radioiodine isotopes in the thyroid[18]. 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[19, 20]. 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 micrometre and nanometre 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[21–24]. 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.

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[25–27]. 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.

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 radio-induced 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[e.g. 28–30]. Among occupationally exposed groups, uranium miners[31–33], Chernobyl liquidators[34, 35], Mayak workers[36], other nuclear workers[37, 38], air crew[39], medical staff[40], etc. are of concern, while other studies include individuals exposed as a consequence of radiotherapy[41–44]. Cohorts that may become more and more important in the future may include offspring cohorts of exposed parents[45]. 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[46]. 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. In order to handle such large-scale studies in reasonable time, the use of laboratory networks as analysis platforms of biosamples should be promoted.

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[47] and non-cancer diseases such as cardiovascular diseases[28], neurological impairments or eye lens opacities[34, 48] 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.

VISION 3: TOWARDS AN EFFICIENT DOSE ASSESSMENT FOR 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.

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 scarce and rapidly change with time. A number of dosimetric improvements are therefore considered important to enable decision makers to initiate the most urgent actions[49–51]. For example, rapid identification of individuals with high risk of developing radiation-induced 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.

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[52]. 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[53, 54].

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[55–61].

VISION 4: TOWARDS INTEGRATED PERSONALISED DOSIMETRY IN MEDICAL APPLICATIONS

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 tumour, varies considerably with many factors, and doses can vary spatially from tens of gray to milligray[62, 63]. 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.

Epidemiological studies of second cancers following radiotherapy require specification of dose to the patient at the site of the subsequent malignancy, making out-of-field dosimetry for photon and particle therapy an important field of dosimetric development[64–77], including the development of analytical models for out-of-field dosimetry calculations[65, 78]. Moreover, because additional 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[73, 74]. 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[64, 70] and hadron radiotherapy where high-energy secondary neutrons are produced[64, 69, 71]. As an ultimate goal of this research, calculation of a complete map of doses for each individual patient would be possible.

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.

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 micrometre and nanometre scale doses of these emitters.

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.

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 optimisation must be considered as key feature of these efforts, especially in view of the rapid development of new CT techniques[79].

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

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.

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.

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.

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[80, 81]. 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.

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.

HARMONISATION

The goal of harmonisation of dosimetric procedures in Europe is central to the overall EURADOS vision. Every strategic objective requires an element of harmonisation, since for all areas of research where dosimetry is required (epidemiology, occupational exposures, environmental monitoring, emergency preparedness, medical applications, etc.) a consistent approach in determining individual doses of exposed subjects and/or ambient dose rates is indispensable.

As far as individual monitoring is concerned, the EC acknowledged the need for harmonisation in dosimetric practices. The Council Directive 96/29 EURATOM (13 May 1996)[82] had major implications for individual monitoring, requesting the approval of dosimetry services, the generalised use of the operational dosimetric quantities and increasing the importance of quality assurance (QA) and quality control (QC) measures and their application to the routine work of individual monitoring services (IMSs). The recent Council Directive 2013/59/EURATOM (5 December 2013)[83] extends this concern to occupational, public, patient and environmental exposures and respective dose assessments.

Accreditation is gradually becoming more and more important in Europe, and QA and QC are a central element. Dose estimates derived from measurements and/or calculations need to be reliable and comparable. Access to reference facilities to ensure calibration, traceability and reliability of results (e.g. quality of measurements and confidence on the results) is essential to guarantee a sustained, long-lasting

and consistent quantification of exposures to ionising radiation.

In this context, intercomparison exercises have been and will be in the future a central element of EURADOS activities. For individual monitoring, it is our vision to create a long-lasting self-sustained system of actions that ensures harmonised dosimetric practices. This would include organisation of intercomparisons for whole-body dosemeters for photon fields every 2–3 years, and with a smaller frequency for extremity dosemeters and neutron dosemeters (3–5 years interval). This would comply with EN/ISO/IEC 17025[84] requirements for accreditation if IMS participate in intercomparison exercises on a regular basis. The experience gained by EURADOS in the realisation of such actions[1–4, 85–87] may prove useful to other organisations such as the International Atomic Energy Agency (IAEA). Collaboration may be useful in organising similar actions in other parts of the world.

In case of a major radiological emergency, an early and reliable assessment of contamination and dose rate levels is of key importance for the protection of the public from external radiation and from intake of radioactivity from foodstuffs. Validation of procedures and the traceable calibration of any detector systems used to supply data to monitoring networks will be required, e.g. European Radiological Data Exchange Platform (EURDEP), European Study of Occupational Radiation Exposure (ESOREX), Radioactivity Environmental Monitoring (REM) database. EURADOS intends to support operators of national early warning dosimetry networks and to consult regulatory bodies and the Joint Research Centre (JRC) Ispra concerning legal aspects of environmental radiation monitoring, especially those related to Articles 35 and 36 of the Euratom Treaty. Cooperation between the Institute for Environment and Sustainability (IES) with regard to EURDEP and EURADOS is considered to be a key element in developing further the idea of harmonisation in environmental monitoring. This will also include definition of standards and publication of technical recommendations.

Monitoring the success of intercomparison exercises[1–4, 85–87] is of course important, and regular surveys should be instigated by EURADOS to document the quality of dosimetric practices in Europe and to compare it to that in other regions of the world[4]. A regular analysis of results must be ensured, reasons for observed deviations be identified and suggestions for an improvement of dosimetric quality be made. This will require up-to-date contact details of interested IMSs. In order to keep dosimetric practices up to date, current and future ICRP and ICRU documents as well as corresponding EU Directives must be continuously scrutinised and their potential implications on measurement quantities, phantoms, etc. evaluated. For example, recent work on radiation effects suggested that the $H_p(3)$ quantity might deserve further attention including QA and QC issues, particularly with the decrease in the corresponding annual dose limit for the lens of the eye. Additionally, any new technical developments with respect to passive and active personal dosemeters must be included in this evaluation.

Doses from intakes of radionuclides are estimated from monitoring data of activity in total/partial body and in excreta samples (urine and faeces) using biokinetic and dosimetric models and from assumptions about the pattern of intake and the properties of the radioactive material inside the body. Past intercomparison exercises[88, 89] have shown a wide range in doses that can be obtained from the same data set from different assessors demonstrating the need for guidance on harmonising internal dose evaluations. Any actions required in this context must take into account the state-of-the-art tools currently available and forthcoming publications such as ICRP/OIR Reports[90], revised IDEAS Guidelines for the Estimation of Committed Doses from Incorporation Monitoring Data[59], ISO Standards in internal dosimetry[91] and the output of the TechRec project *Technical Recommendations for Monitoring Individuals Occupationally Exposed to Internal Radiation* currently being prepared for the EC by a consortium of EURADOS voting member institutions.

Computational methods form a part of the work programme of all EURADOS WGs. These methods have moved from the domain of experts to become routine tools. Questionnaires performed by EURADOS in the past showed the poor level of QA performed by those using these methods. This situation is likely to become even more critical in the future because it is likely that these methods will become more and more widespread. Intercomparisons have already been performed by EURADOS on modelling tasks ranging from simulations of accelerators to unfolding of neutron energy distributions, all of which have shown the potential for good agreement between solutions and also the potential for large systematic errors in results[92–94]. EURADOS will continue to perform modelling intercomparisons, commonly as collaborations between WGs.

EDUCATION AND TRAINING

Education and training have always been a key issue in EURADOS activities. Consequently, EURADOS organises regularly specific training events like training courses, winter schools and scientific symposia. Training courses are related to specific topics in the field of the EURADOS WGs, usually last for 3–5 days, with limited participation to about 40 attendees. EURADOS *Winter Schools* have taken place at the EURADOS Annual Meeting since 2007. They

usually last up to 1 day and provide 'refresher courses' on topics relevant to radiation dosimetry. These efforts will continue in the future, and every year a general topic that is thought to be important for the EURADOS community will be identified. In contrast, scientific symposia are usually related to research topics or results from EURADOS WGs or related research projects. Proceedings of the symposia have been published in peer-reviewed journals[95–102]. These actions will also continue in an effort to present new research findings gained from various EURADOS WGs actions.

Implementation of the EC directives and technical recommendations[103] into practice is an important element of harmonisation[104, 105]. For this reason, EURADOS has prepared a training course on 'Implementation of RP 160 and on lessons learned from intercomparison exercises'. This course was held for the first time in 2012 in Krakow, Poland. Among others, the course was very instrumental in defining the future strategy needed for a better harmonisation of dosimetric practice, and the need for more practical information on (a) the work necessary to apply for accreditation, (b) information on how to use the results of type testing and/or intercomparisons in the uncertainty budgets and (c) guidance on a practical assessment of uncertainties was emphasised. Future training actions in this field will be based on this experience and on the input by the IMS community. On the other hand, the analysis of QA/QC surveys organised on a regular basis is a means of identifying topics where training actions might be needed and welcomed by IMS.

Training on fundamentals of internal dosimetry will be required in many scenarios, covering knowledge about quantities, monitoring techniques, biokinetics of incorporated radionuclides, interpretation of monitoring data, dose assessment, uncertainties and quality management. Reference publications, software and other tools required are, among others, ICRP OIR reports, ISO Standards, IDEAS Guidelines, NCRP Models and Reports.

In summary, EURADOS education and training actions are generally organised in an effort to maintain the competence in the field of dosimetry in Europe. These actions are considered important and will be continued in the future including training on upcoming new dosimetric techniques. Coordination with education and training (E&T) efforts of other research platforms is recommended in order to guarantee efficient use of techniques in dosimetry in all relevant research disciplines where exposure quantification is needed.

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REFERENCES

1. Grimbergen, T. W. M., Figel, M., Romero, A. M., Stadtmann, H. and McWhan, A. F. *EURADOS self-sustained programme of intercomparisons for individual monitoring services*. Radiat. Prot. Dosim. **144**(1–4), 266–274 (2011).
2. Fantuzzi, E., Chevallier, M.-A., Cruz-Suarez, R., Luszik-Bhadra, M., Mayer, S., Thomas, D. J., Tanner, R. and Vanhavere, F. *EURADOS IC2012N: EURADOS 2012 intercomparison for whole-body neutron dosimetry*. Radiat. Prot. Dosim. **161**, 73–77 (2014).
3. Stadtmann, H., McWhan, A., Figel, M., Dobrzynska, W., Grimbergen, T. and Romero, A. M. *EURADOS intercomparisons for individual monitoring services: results of the 2012 whole body intercomparison*. Radiat. Meas. **71**, 416–420 (2014).
4. Gilvin, P., Alves, J. G., Cherestes, C., van Dijk, J., Lehtinen, M., Rossi, F. and Vekic, B. *Quality assurance in individual monitoring: a summary of the EURADOS survey 2012*. Radiat. Meas. **71**, 434–437 (2014).
5. International Commission on Radiation Measurements and Units (ICRU). *Quantities and Units in Radiation Protection Dosimetry (Report 51)* (1993).
6. International Commission on Radiological Protection (ICRP). *1990 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 60. Ann. ICRP, 21 (1991).
7. International Commission on Radiological Protection (ICRP). *The 2007 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 103. Ann. ICRP, 37 (2007).
8. Fulford, J., Nikjoo, H., Goodhead, D. T. and O'Neill, P. *Yields of SSB and DSB induced in DNA by Al(K) ultrasoft X-rays and alpha-particles: comparison of experimental and simulated yields*. Int. J. Radiat. Biol. **77**, 1053–1066 (2001).
9. Goodhead, D. T. and Nikjoo, H. *Track structure analysis of ultrasoft X-rays compared to high- and low-LET radiations*. Int. J. Radiat. Biol. **55**, 513–529 (1989).
10. Cucinotta, F. A., Nikjoo, H. and Goodhead, D. T. *Model for radial dependence of frequency distributions for energy imparted in nanometer volumes from HZE particles*. Radiat. Res. **153**, 459–468 (2000).
11. Bashkirov, V., Schulte, R., Breskin, A., Chechnik, R., Schemelinin, S., Garty, G., Wroe, A., Sadrozinski, H. and Grosswendt, B. *Ion-counting nanodosemeter with particle tracking capabilities*. Radiat. Prot. Dosim. **122**, 415–419 (2006).
12. Shagina, N. B., Tolstykh, E. and Degteva, M. O. *Improvements in the biokinetic model for strontium with allowance for age and gender differences in bone mineral metabolism*. Radiat. Prot. Dosim. **105**(1–4), 619–622 (2003).
13. Bijwaard, H., Brugmans, M. J. P. and Leenhouts, H. P. *Two-mutation models for bone cancer due to radium, strontium and plutonium*. Radiat. Res. **162**, 171–184 (2004).

14. Luciani, A. and Polig, E. *Surface-seeking radionuclides in the skeleton: current approach and recent developments in biokinetic modelling for humans and beagles.* Radiat. Prot. Dosim. **127**(1–4), 140–13 (2007).
15. Hofmann, W., Fakir, H. and Pihet, P. *Internal microdosimetry of inhaled radon progeny in bronchial airways: advantages and limitations.* Radiat. Prot. Dosim. **127**, 40–45 (2007).
16. Farkas, A., Hofmann, W., Báláshazy, I., Szöke, I., Madas, B. G. and Moustafa, M. *Effect of site-specific bronchial radon progeny deposition on the spatial and temporal distribution of cellular responses.* Radiat. Environ. Biophys. **50**, 281–297 (2011).
17. Truta-Popa, L. A., Cosma, C. and Hofmann, W. *Prediction of lung cancer risk for radon exposures based on cellular alpha particle hits.* Radiat. Prot. Dosim. **145**, 218–223 (2011).
18. Li, W. B., Friedland, W., Pomplun, E., Jacob, P., Paretzke, H. G., Lassmann, M. and Reiners, C. *Track structures and dose distributions from decays of ^{131}I and ^{125}I in and around water spheres simulating micrometastases of differentiated thyroid cancer.* Radiat. Res. **156**(4), 419–429 (2001).
19. Szőke, I., Balásházy, I., Farkas, Á. and Hofmann, W. *The effect of inhomogeneous activity distributions and airway geometry on cellular doses in radon lung dosimetry.* Radiat. Prot. Dosim. **127**(1–4), 68–72 (2007).
20. Szőke, I., Farkas, Á., Balásházy, I. and Hofmann, W. *Modelling of cell deaths and cell transformations of inhaled radon in homes and mines based on a biophysical and microdosimetric model.* Int. J. Radiat. Biol. **84**(2), 127–138 (2008).
21. Seymour, C. and Mothersill, C. *Cell communication and the "bystander effect".* Radiat. Res. **151**, 505–506 (1999).
22. Brenner, D. J., Little, J. B. and Sachs, R. K. *The bystander effect in radiation oncogenesis: II. A quantitative model.* Radiat. Res. **155**, 402–408 (2001).
23. Szőke, I., Farkas, Á., Balásházy, I. and Hofmann, W. *3D-modeling of radon-induced cellular radiobiological effects in bronchial airway bifurcations: direct versus bystander effects.* Int. J. Radiat. Biol. **88**(6), 477–492 (2012).
24. Belchior, A., Balásházy, I., Monteiro Gil, O., Almeida, P. and Vaz, P. *Does the number of irradiated cells influence the spatial distribution of bystander effects?* Dose Response **12**(4), 525–239 (2014).
25. International Commission on Radiological Protection (ICRP). *Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures.* ICRP Publication 116; Ann. ICRP 40(2–5) (2010).
26. International Commission on Radiation Measurements and Units. *Conversion Coefficients for Use in Radiological Protection Against External Radiation.* ICRU Report 57 (1998).
27. International Commission on Radiological Protection (ICRP). *Adult Reference Computational Phantoms.* ICRP Publication 110. Ann. ICRP 39 (2009).
28. Ozasa, K., Shimizu, Y., Suyama, A., Kasagi, F., Soda, M., Grant, E. J., Sakata, R., Sugiyama, H. and Kodama, K. *Studies of the mortality of atomic bomb survivors, Report 14, 1950–2003: an overview of cancer and noncancer diseases.* Radiat. Res. **177**, 229–243 (2012).
29. Krestinina, L. Y., Epifanova, S., Silkin, S., Mikryukova, L., Degteva, M., Shagina, N. and Akleyev, A. *Chronic low-dose exposure in the Techa River Cohort: risk of mortality from circulatory diseases.* Radiat. Environ. Biophys. **52**(1), 47–57 (2013).
30. Ivanov, V. K., Kashcheev, V. V., Chekin, S. Y., Maksioutov, M. A., Tumanov, K. A., Vlasov, O. K., Shchukina, N. V. and Tsyb, A. F. *Radiation-epidemiological studies of thyroid cancer incidence in Russia after the Chernobyl accident (estimation of radiation risks, 1991–2008 follow-up period).* Radiat. Prot. Dosim. **151**(3), 489–499 (2012).
31. Drubay, D., Ancelet, S., Acker, A., Kreuzer, M., Laurier, D. and Rage, E. *Kidney cancer mortality and ionizing radiation among French and German uranium miners.* Radiat. Environ. Biophys. **53**(3), 505–513 (2014).
32. Kreuzer, M., Dufey, F., Sogl, M., Schnelzer, M. and Walsh, L. *External gamma radiation and mortality from cardiovascular diseases in the German WISMUT uranium miners cohort study, 1946–2008.* Radiat. Environ. Biophys. **52**(1), 37–46 (2013).
33. Tomasek, L., Rogel, A., Tirmarche, M., Mitton, N. and Laurier, D. *Lung cancer in French and Czech uranium miners: radon-associated risk at low exposure rates and modifying effects of time since exposure and age at exposure.* Radiat Res. **169**, 125–137 (2008).
34. Worgul, B. V. *et al. Cataracts among Chernobyl clean-up workers: implications regarding permissible eye exposures.* Radiat. Res. **167**, 233–243 (2007).
35. Ivanov, V. K., Tsyb, A. F., Khait, S. E., Kashcheev, V. V., Chekin, S. Y., Maksioutov, M. A. and Tumanov, K. A. *Leukemia incidence in the Russian cohort of Chernobyl emergency workers.* Radiat. Environ. Biophys. **51**, 143–149 (2012).
36. Gilbert, E. S., Sokolnikov, M. E., Preston, D. L., Schonfeld, S. J., Schadilov, A. E., Vasilenko, E. K. and Koshurnikova, N. A. *Lung cancer risks from plutonium: an updated analysis of data from the Mayak worker cohort.* Radiat. Res. **179**, 332–342 (2013).
37. Cardis, E., Vrijheid, M., Blettner, M., Gilbert, E., Hakama, M., Hill, C., Howe, G., Kaldor, J., Muirhead, C. R. and Schubauer-Berigan, M. *The 15-country collaborative study of cancer risk among radiation workers in the nuclear industry: estimates of radiation-related cancer risks.* Radiat. Res. **167**, 396–416 (2007).
38. Muirhead, C. R., O'Hagan, J. A., Haylock, R. G. E., Phillipson, M. A., Willcock, T., Berridge, G. L. C. and Zhang, W. *Mortality and cancer incidence following occupational radiation exposure: third analysis of the National Registry for Radiation Workers.* Br. J. Cancer **100**, 206–212 (2009).
39. Hammer, G. P. *et al. Mortality from cancer and other causes in commercial airline crews: a joint analysis of cohorts from 10 countries.* Occup. Environ. Med. **71**, 313–322 (2014).
40. Little, M. P. *et al. Association of chromosome translocation rate with low dose occupational radiation exposures in U.S. radiologic technologists.* Radiat. Res. **182**, 1–17 (2014).
41. Boaventura, P., Oliveira, R., Pereira, D., Soares, P. and Teixeira-Gomes, J. *Head and neck basal cell carcinoma prevalence in individuals submitted to childhood X-ray*

epilation for tinea capitis treatment. Eur. J. Dermatol. **22**, 225–230 (2012).
42. Eidemüller, M., Holmberg, E., Jacob, P., Lundell, M. and Karlsson, P. *Breast cancer risk after radiation treatment at infancy: potential consequences of radiation-induced genomic instability*. Radiat. Prot. Dosim. **143**, 375–379 (2011).
43. Preston, D. L., Mattsson, A., Holmberg, E., Shore, R., Hildreth, N. G. and Boice, J. D. Jr. *Radiation effects on breast cancer risk: a pooled analysis of eight cohorts*. Radiat. Res. **158**(2), 220–235 (2002), and Erratum in Radiat. Res. 158, 666 (2002).
44. Ron, E., Lubin, J. H., Shore, R. E., Mabuchi, K., Modan, B., Pottern, L. M., Schneider, A. B., Tucker, M. A. and Boice, J. D. Jr. *Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies*. Radiat. Res. **141**, 259–277 (2012).
45. Napier, B. A. *Joint U.S./Russian studies of population exposures resulting from nuclear production activities in the southern Urals*. Health Phys. **106**, 294–304 (2014).
46. Berrington de Gonzalez, A., Gilbert, E., Curtis, R., Inskip, P., Kleinerman, R., Morton, L., Rajaraman, P. and Little, M. P. *Second solid cancers after radiation therapy: a systematic review of the epidemiologic studies of the radiation dose-response relationship*. Int. J. Radiat. Oncol. Biol. Phys. **86**, 224–233 (2013).
47. Wakeford, R. and Little, M. P. *Risk coefficients for childhood cancer after intrauterine irradiation: a review*. Int. J. Radiat. Biol. **79**, 293–309 (2013).
48. Neriishi, K., Nakashima, E., Akahoshi, M., Hida, A., Grant, E. J., Masunari, N., Funamoto, S., Minamoto, A., Fujiwara, S. and Shore, R. E. *Radiation dose and cataract surgery incidence in atomic bomb survivors, 1986–2005*. Radiology **265**, 167–174 (2012).
49. Ainsbury, E. A. *et al. Retrospective dosimetry techniques for external radiation exposures*. Radiat. Prot. Dosim. **147**, 573–592 (2011).
50. International Atomic Energy Agency. *Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies*. EPR-Biodosimetry, IAEA (2011).
51. Fattibene, P. and Wojcik, A. *Biodosimetric tools for a fast triage of people accidentally exposed to ionising radiation*. Ann. Ist. Super. Sanità. **45**(3), 245–312 (2009).
52. Romm, H. *et al. Automatic scoring of dicentric chromosomes as a tool in large scale radiation accidents*. Mutat. Res. **756**, 174–183 (2013).
53. Kulka, U. *et al. Realising the European network of biodosimetry: RENEB—status quo*. Radiat. Prot. Dosim. **164**(1–2), 42–45 (2015).
54. Carr, Z. *WHO-REMPAN for global health security and strengthening preparedness and response to radiation emergencies*. Health Phys. **98**, 773–778 (2010).
55. Giussani, A., Blanchardon, E., Breustedt, B., Fritsch, P., Hoeschen, C. and Lopez, M. A. *Developing a physiologically based approach for modeling plutonium decorporation therapy with DTPA*. Int. J. Radiat. Biol. **21**, 1–16 (2014).
56. Breustedt, B. *et al. The CONRAD approach to biokinetic modeling of DTPA decorporation therapy*. Health Phys. **99**(4), 547–552 (2010).
57. Li, W. B., Klein, W., Blanchardon, E., Puncher, M., Leggett, R. W., Oeh, U., Breustedt, B., Noßke, D. and Lopez, M. A. *Parameter uncertainty analysis of a biokinetic model of caesium*. Radiat. Prot. Dosim. **163**(1), 37–57 (2015).
58. Vrba, T. *et al. EURADOS intercomparison exercise on MC modelling for the in-vivo monitoring of Am-241 in skull phantoms (Part I)*. R. Radiat. Phys. Chem. **104**, 332–338 (2014).
59. Castellani, C. M., Marsh, J. W., Hurtgen, C., Blanchardon, E., Berard, P., Giussani, A. and Lopez, M. A. *IDEAS Guidelines (version 2) for the Estimation of Committed Doses from Incorporation Monitoring Data*. EURADOS Report 2013-01. Braunschweig, (2013). ISSN 2226-8057. ISBN 978-3-943701-03-6.
60. Szőke1, I., Farkas, A., Balásházy, I. and Hofmann, W. *Stochastic aspects of primary cellular consequences of radon inhalation*. Radiat. Res. **171**(1), 96–106 (2009).
61. Balásházy, I. and Hofmann, W. *Quantification of local deposition patterns of inhaled radon decay products in human bronchial airway bifurcations*. Health Phys. **78**(2), 147–158 (2000).
62. Hall, E. J. *Intensity-modulated radiation therapy, protons and the risk of second cancers*. Int. J. Radiat. Oncol. Biol. Phys. **65**, 1–7 (2006).
63. Harrison, R. M. *Introduction to dosimetry and risk estimation of second cancer induction following radiotherapy*. Radiat. Meas. **57**, 1–8 (2013).
64. Newhauser, W. D. and Durante, M. *Assessing the risk of second malignancies after modern radiotherapy*. Nat. Rev. Cancer **11**, 439–448 (2011).
65. Kry, S. F., Titt, U., Followill, D., Pönisch, F., Vassiliev, O. N., White, R. A., Stovall, M. and Salehpour, M. *A Monte Carlo model for out-of-field dose calculation from high-energy photon therapy*. Med. Phys. **34**, 3489–3499 (2007).
66. Sharma, S. D., Upreti, R. R. and Deshpande, D. D. *Use of peripheral dose data from uniform dynamic multileaf collimation fields to estimate out-of-field organ dose in patients treated employing sliding window intensity-modulated radiotherapy*. Phys. Med. Biol. **51**, 2987–2995 (2006).
67. Petti, P. L., Chuang, C. F., Smith, V. and Larson, D. A. *Peripheral doses in CyberKnife radiosurgery*. Med. Phys. **33**, 1770–1779 (2006).
68. Miljanić, S. *et al. Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: results for photons*. Radiat. Meas. **57**, 35–47 (2013).
69. Di Fulvio, A., Tana, L., Domingo, C., de San Pedro, M., d'Agostino, E. and d'Errico, F. *Clinical simulations of prostate radiotherapy using BOMAB-like phantoms: results for neutrons*. Radiat. Meas. **57**, 48–61 (2013).
70. Mansur, D. B., Klein, E. E. and Maserang, B. P. *Measured peripheral dose in pediatric radiation therapy: a comparison of intensity-modulated and conformal techniques*. Radiother. Oncol. **82**, 179–184 (2007).
71. Kry, S. F., Salehpour, M., Followill, D. S., Stovall, M., Kuban, D. A., White, R. A. and Rosen, I. I. *Out-of-field photon and neutron dose equivalents from step-and-shoot intensity-modulated radiation therapy*. Int. J. Radiat. Oncol. Biol. Phys. **62**, 1204–1216 (2005).
72. Howell, R. M., Scarboro, S. B., Taddei, P. J., Krishnan, S., Kry, S. F. and Newhauser, W. D. *Methodology for determining doses to in-field, out-of-field and partially in-field organs for late effects studies in photon radiotherapy*. Phys. Med. Biol. **55**, 7009–7023 (2010).

73. Harrison, R. M., Wilkinson, M., Shemilt, A., Rawlings, D. J., Moore, M. and Lecomber, A. R. *Organ doses from prostate radiotherapy and associated concomitant exposures*. Br. J. Radiol. **79**, 487–496 (2006).
74. Harrison, R. M., Wilkinson, M., Rawlings, D. J. and Moore, M. *Doses to critical organs following radiotherapy and concomitant imaging of the larynx and breast*. Br. J. Radiol. **80**, 989–995 (2007).
75. D'Agostino, E., Bogaerts, R., Defraene, G., de Freitas Nascimento, L., Van den Heuvel, F., Verellen, D., Duchateau, M. and Vanhavere, F. *Peripheral doses in radiotherapy: a comparison between IMRT and tomotherapy*. Radiat. Meas. **57**, 62–67 (2013).
76. La Tessa, C. *et al*. *Out-of-field dose studies with an anthropomorphic phantom: comparison of X-rays and particle therapy treatments*. Radiother. Oncol. **105**, 133–138 (2012).
77. Xu, X. G., Bednarz, B. and Paganetti, H. *A review of dosimetry studies on external-beam radiation treatment with respect to second cancer induction*. Phys. Med. Biol. **53**, R193–R241 (2008).
78. van der Giessen, P. *Peridose: a software program to calculate the dose outside the primary beam in radiation therapy*. Radiother. Oncol. **58**, 209–213 (2001).
79. Dougeni, E., Faulkner, K. and Panayiotakis, G. *A review of patient dose and optimisation methods in adult and paediatric CT scanning*. Eur. Jour. Rad. **81**, 665–683 (2012).
80. Tanner, R. J. *et al*. *Achievements in workplace neutron dosimetry in the last decade: lessons learned from the EVIDOS project*. Radiat. Prot. Dosim. **126**, 471–476 (2007).
81. Luszik-Bhadra, M. *et al*. *Characterisation of mixed neutron-photon workplace fields at nuclear facilities by spectrometry (energy and direction) within the EVIDOS project*. Radiat. Prot. Dosim. **124**, 219–229 (2007).
82. Council Directive 1996/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Official Journal of the European Union L159 June (1996).
83. Council Directive 2013/59/Euratom of 5 December 2013 laying down the basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Official Journal of the European Union L13 (2014).
84. EN ISO/IEC 17025. *General Requirements for the Competence of Testing and Calibration Laboratories*. International Organization for Standardization and International Electrotechnical Comission (2005).
85. Grimbergen, T. W. M., Figel, M., Romero, A. M., Stadtmann, H. and McWhan, A. F. *EURADOS Intercomparison 2008 for Whole Body Dosemeters in Photon Fields EURADOS Report 2012-01, EURADOS*. Braunschweig (2012).
86. Grimbergen, T. W. M., Figel, M., Romero, A. M., Stadtmann, H. and McWhan, A. F. *EURADOS Intercomparison 2009 for Extremity Dosemeters in Photon and Beta Fields*. EURADOS Report 2013-03, EURADOS, Braunschweig (2013).
87. Fantuzzi, E., Chevallier, M. A., Cruz-Suarez, R., Luszik-Bhadra, M., Mayer, S., Thomas, D. J., Tanner, R. and Vanhavere, F. *EURADOS Intercomparison 2012 for Whole-Body Neutron Dosemeters*. EURADOS Report 2014-xxx, EURADOS, Braunschweig (2014).
88. Castellani, C. M., Lopez, M. A., Luciani, A., Marsh, J. W., Vrba, T. and Cruz-Suarez, R. *Results of an internal dose assessment intercomparison exercise after a EURADOS/IAEA training course*. Radiat. Prot. Dosim. **114**, 592–595 (2011).
89. Lopez, M. A. *et al*. *EURADOS Intercomparison on measurements and Monte Carlo modeling for the assessment of Americium in a USTUR leg phantom*. Radiat. Prot. Dosim. **114**, 295–299 (2011).
90. Eckerman, K., Harrison, J., Menzel, H.-G. and Clement, C. H. *Compendium of Dose Coefficients Based on ICRP Publication 60*. ICRP publication 119, Ann. ICRP 41, supp 1 (2012).
91. International Organization for Standardization. ISO 27048:2011, *Radiation protection – Dose Assessment for the Monitoring of Workers for Internal Radiation Exposure*, ISO, Geneva (2011).
92. Siebert, B. R. L. *et al*. *Pitfalls and modelling inconsistencies in computational radiation dosimetry: lessons learnt from the QUADOS intercomparison. Part I: neutrons and uncertainties*. Radiat. Prot. Dosim. **118**, 144–154 (2006).
93. Price, R. A. *et al*. *Pitfalls and modelling inconsistencies in computational radiation dosimetry: lessons learnt from the QUADOS intercomparison. Part II: photons, electrons and protons*. Radiat. Prot. Dosim. **118**, 155–166 (2006).
94. Rollet, S., Agosteo, S., Fehrenbacher, G., Hranitzky, C., Radon, T. and Wind, M. *Intercomparison of radiation protection devices in a high-energy stray neutron field, Part I: Monte Carlo simulations*. Radiat. Meas., **44**, 649–659 (2009).
95. Stather, J. W., Hopewell, J. and Pihet, P. *Biological and physical dosimetry for radiation protection (AM2004)*. Radiat. Prot. Dosim. **112**(4), 455–545 (2004).
96. Olko, P., Schuhmacher, H. and Zoetelief, J. *Radiation protection dosimetry and dosimetry for medical applications (AM2005)*. Radiat. Prot. Dosim. **118**(2), 137–229 (2006).
97. Thomas, D. J., Bartlett, D. T., Fantuzzi, E. and Zoetelief, J. *Uncertainties in dosimetry – principles through to practice (AM2006)*. Radiat. Prot. Dosim. **121**(1), 1–82 (2006).
98. Lopez, M. A., Fantuzzi, E., Gomez-Ros, J. M., Romero, A. and Vanhavere, F. *Characterization of workplaces for the assessment of the doses to individuals (AM2007)*. Radiat. Prot. Dosim. **124**(3), 211–285 (2007).
99. Barthe, J., Bottollier-Depois, J. F., d'Ericco, F., Fantuzzi, E. and Vanhavere, F. *Dosimetric issues in the medical use of ionizing radiation (AM2008)*. Radiat. Prot. Dosim. **131**(1), 1–153 (2008).
100. Bottollier-Depois, J. F., Beck, P., Reitz, G., Rühm, W. and Wissmann, F. *Cosmic radiation and aircrew exposure (AM2009)*. Radiat. Prot. Dosim. **136**(4), 231–328 (2009).
101. Esposito, A. *Accelerator radiation protection and shielding (AM2010)*. Radiat. Prot. Dosim. **146**(4), 371–450 (2011).
102. Harrison, R. *Dosimetry for second cancer risk estimation in radiotherapy (AM2012)*. Rad. Meas. **57**, 1–74 (2013).

103. *Radiation Protection 160 European Technical Recommendations for Monitoring Individuals Occupationally Exposed to External Radiation*. DG Energy, (2009).
104. Alves, J. G., Ambrosi, P., Bartlett, D. T., Currivan, L., van Dijk, J. W., Fantuzzi, E. and Kamenopoulou, V. *The new EC technical recommendations for monitoring individuals occupationally exposed to external radiation*. Radiat. Prot. Dosim. **144**, 17–25 (2011).
105. van Dijk, J. W. E., Alves, J. G., Ambrosi, P., Bartlett, D. T., Currivan, L., Fantuzzi, E. and Kamenopoulou, V. *A review of new European technical recommendations for monitoring individuals occupationally exposed to external radiation*. Rad. Meas. **55**, 30–33 (2013).