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P. Fattibene, Ž. Knežević, M.A. Lopez, S. Mayer,
S. Miljanić, S. Neumaier, P. Olko,
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W. Rühm[1], E. Fantuzzi[2], R. Harrison[3], H. Schuhmacher[4], F. Vanhavere[5], J. Alves[6], J.F. Bottollier-Depois[7], P. Fattibene[8], Ž. Knežević[9], M.A. Lopez[10], S. Mayer[11], S. Miljanić[9], S. Neumaier[4], P. Olko[12], H. Stadtmann[13], R. Tanner[14], C. Woda[1]

[1] Helmholtz Center Munich, Institute of Radiation Protection, Neuherberg, Germany

[2] ENEA, Radiation Protection Institute, Bologna, Italy

[3] University of Newcastle, Newcastle, UK

[4] Physikalisch Technische Bundesanstalt (PTB), Braunschweig, Germany

[5] Belgian Nuclear Research Centre (SCK-CEN), Mol, Belgium

[6] Instituto Superior Técnico (IST), CTN, Portugal

[7] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses Cedex, France

[8] Istituto Superiore di Sanità (ISS), Rome Italy

[9] Ruđer Bošković Institute (RBI), Zagreb, Croatia

[10] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Madrid, Spain

[11] Paul Scherer Institut (PSI), Villigen, Switzerland

[12] Instytut Fizyki Jądrowej (IFJ), Krakow, Poland

[13] Seibersdorf Laboratories, Seibersdorf, Austria

[14] Public Health England, Chilton, Didcot, United Kingdom

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Bundesallee 100
38116 Braunschweig
Germany
office@EURADOS.org
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# 1 Foreword

The European Radiation Dosimetry Group (EURADOS) comprises a self-sustainable network of more than 60 European institutions and 300 scientists active in the field of radiation dosimetry. The aim of the network is to promote research and development and European cooperation in the field of dosimetry of ionizing radiation. For this, EURADOS has established Working Groups (WGs) in various dosimetric disciplines such as harmonization of individual monitoring, environmental dosimetry, computational dosimetry, internal dosimetry, dosimetry for medical applications, retrospective dosimetry, and dosimetry in high energy radiation fields.

In autumn 2012 EURADOS decided to develop a Strategic Research Agenda (SRA) which will contribute to the identification of future research needs in radiation dosimetry. The SRA of EURADOS will be used as a guideline for the activities of the Working Groups. Moreover, the EURADOS SRA is an input to the recently launched OPERRA (Open Project for European Radiation Research Area) project 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 are also expected to benefit from this SRA.

Since autumn 2012, each EURADOS WG has 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 20013 in Barcelona, Spain, the EURADOS Council established an SRA Working Group (members: W. Rühm (chair), E. Fantuzzi, R. Harrison, H. Schuhmacher, F. Vanhavere) who put together all collected information and – after the July 2013 Council meeting in Berlin, Germany – began to draft the SRA.

The present document formulates – based on input from EURADOS Working Group members – five visions in dosimetry and defines key issues in dosimetry research that are considered important for the next decades, for radiation research in Europe. This document was prepared for the EURADOS Annual Meeting to be held in Budapest, Hungary, in February 2014, where it was further discussed both at the EURADOS General Assembly and at Working Group meetings. A round of input from the EURADOS voting members was also organised. Thereafter the document was finalized and published as the EURADOS Strategic Research Agenda (first version). This version will then be the basis for a second round of improvement including stakeholder input.

The present SRA was put together by the EURADOS Editorial Group on "Developing a Strategic Research Agenda". The authors of this SRA (members of this group, members of the EURADOS Council, and the Working Group chairs) appreciate the input from the various EURADOS Working Groups.

# 2 Executive Summary

The European Radiation Dosimetry Group (EURADOS) comprises a self-sustainable network of more than 60 European institutions such as reference and research laboratories, dosimetry services and companies, as well as more than 300 scientists active in the field of radiation dosimetry. The aim of the network is to promote research and development and European cooperation in the field of dosimetry of ionizing 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 (WG) on various dosimetric disciplines such as harmonization of individual monitoring, environmental dosimetry, computational dosimetry, internal dosimetry, dosimetry for medical applications, retrospective dosimetry, and dosimetry in high energy radiation fields. These groups 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 fields of applications of ionizing radiation needed to contribute to science-based policy recommendations in this area. The aspect of harmonization and education and training are also very important activities for EURADOS, by the organization of intercomparisons and training courses.

At the end of 2012, EURADOS initiated a process for the development of a Strategic Research Agenda (SRA) which is designed to define which topics, if critically addressed over the next decades, are needed to significantly advance dosimetry in various applications. In the future, the EURADOS SRA will be an input for the recently launched OPERRA (Open Project for European Radiation Research Area) project 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 are also expected to benefit from this SRA. The efforts of EURADOS to develop an SRA for dosimetry, complement efforts of other 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.

Although the present document was 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), associations from the medical field and the International Organization for Standardization (ISO), because a number of EURADOS members are also members in these institutions. A more formal process of stakeholder involvement will be initiated at a later stage of SRA development.

The present document formulates – based on input from EURADOS Working Group members – five visions in dosimetry and defines – for each vision – two to five challenges that are worked out in more detail by means of specific research lines.

Vision 1: Towards updated fundamental dose concepts and quantities

- To improve understanding of spatial correlations of radiation interaction events
- To establish correlations between track structure and radiation damage
- To improve understanding of radiation-induced effects from internal emitters
- To update operational quantities for external exposure

Vision 2: Towards improved radiation risk estimates deduced from epidemiological cohorts

- To improve exposure pathways not yet considered or validated
- To improve retrospective dosimetry for exposure pathways already considered

Vision 3: Towards an efficient dose assessment for radiological emergencies

- To identify and characterize new markers of exposure
- To develop strategies and methods to increase measurement capacity
- To quantify doses after accidental internal contamination

Vision 4: Towards integrated personalized dosimetry in medical applications

- To improve out-of-field dosimetry for photon and particle therapy
- To develop microdosimetric models for imaging and radiotherapy
- To improve dosimetry in modern external beam radiotherapy
- To optimize dose and risk estimations in interventional radiology
- To establish reliable patient dosimetry in CT examinations

Vision 5: Towards improved radiation protection of workers and the public

- To implement new biokinetic models for intake of radionuclides
- To develop calibration procedures for partial body counters
- To develop accurate and on-line personal dosimetry for workers
- To improve neutron dosimetry techniques
- To include nuclide-specific information in dose rate measurements in the environment

Because an important aim of EURADOS is to keep, circulate and improve knowledge in the field of dosimetry, EURADOS organizes training and education actions such as Winter Schools, Scientific Symposia and Training Courses. These actions are also described and future needs are discussed.

Harmonisation of dosimetric practices in Europe is an additional field that is an important part of the EURADOS mission. Scientific work must generate reliable and reproducible results. Harmonization as applied to the deliverables of research work will enhance the consistency and coherence of scientific results, increasing reliability and improving accuracy. For this reason, actions such as intercomparisons and surveys of practices are described here in a separate chapter and their importance in future activities is highlighted.

# 3 Strategic Research Agenda

## 3.1 Towards updated fundamental dose concepts and quantities

To protect humans and the environment from excessive exposure to ionizing radiation, it has been necessary to develop systems for quantifying the radiation and its likely effects. The absorbed dose, the mean value of the energy imparted by ionizing radiation to a volume of interest divided by the mass of that volume, is defined on pure physical grounds, and generally provides a "quantitative description" of the interaction between ionizing radiation and exposed materials. However, for the purpose of radiation protection, the absorbed dose is not based on an adequately detailed description of the energy deposition for correlation with biological consequences. This inadequacy is due to the interplay of several factors: First, the dose-response relation for a particular biological system depends on the radiation quality, i.e. the spectrum of particles and their energies, and the stochastic pattern of energy deposition. Second, different biological systems, such as e.g. different tissue types in the human body, have different susceptibilities for producing radiation-induced effects. Third, as many biological processes are non-linear, the overall response of a biological system may be significantly different for inhomogeneous exposure. For the same reason, the biological consequences of an exposure may also differ depending on the temporal pattern of the irradiation (effects of dose rate and fractionation).

In current radiation protection practice, the issue of radiation quality is taken into account for external exposures through the pragmatic approach of the operational quantities, developed by the International Commission on Radiation Units and Measurements (ICRU), which are based on the *dose equivalent, H*, obtained from the absorbed dose by introducing quality factors that are defined as functions of the linear energy transfer (LET) of the radiation involved.

On the other hand, ICRP has defined a set of protection quantities that could be applied to all relevant exposure situations (internal and external, exposures with various radiation qualities, etc.). For these, the contributions to absorbed dose from different radiation qualities are multiplied by appropriate radiation weighting factors and added to obtain the *equivalent dose*, $H_T$, in an organ or tissue, which in turn is multiplied by tissue weighting factors and summed over all organs and tissues, to obtain the *effective dose, E*. Additionally, for radiation protection purposes, the linear-no-threshold (LNT) hypothesis is assumed to be valid.

A major challenge to this current-practice dosimetric system arises from radioactive material incorporated in biological systems. The incorporation may result from unintentional uptake of natural or anthropogenic radionuclides from the environment or from the administration of radionuclides to an individual for diagnostic or therapeutic purposes. In all cases, the internally deposited energy is highly heterogeneous due to the uptake, biokinetics, retention and physical characteristics of the incorporated radionuclide and the transport within the body of the radiation emitted due to its decay. Therefore, averaging over certain tissues and organs as done for the calculation of *E* might be too simple.

The goal should therefore be to provide physically and conceptually sound quantities to be used in radiation protection. The current system of dose quantities has unnecessary complexity and incoherence and a system of radiation protection quantities that avoids the unnecessary duality of dose equivalents vs. equivalent dose is desirable.

For the vision of updated fundamental dose concepts and quantities the following challenges were identified:

- To improve the understanding of spatial correlations of radiation interaction events
- To quantify correlations between track structure and radiation damage
- To improve the understanding of the biokinetics of internal emitters
- To update operational quantities for external exposure

These challenges are described in detail in the following.

### *3.1.1 To improve understanding of spatial correlations of radiation interaction events*

**Introduction**

The dependence of biological effectiveness on radiation quality is commonly believed to be related to the differences in the energy deposition pattern on a microscopic scale. For charged particles, this pattern is called the track structure, where the loci of interaction events are concentrated around the primary particle trajectory. For photon irradiation, the pattern is given by the tracks produced by the electrons (and positrons) liberated in inelastic photon interactions, and for neutrons by the tracks of the recoil protons. At higher primary particle energies, further secondary particles produced such as alpha particles might also be of relevance. Information on spatial distribution and correlation of secondary particles from models (validated by measurements) should be important, for a fundamental understanding of microscopic dose and dose concepts and the associated uncertainties.

Microdosimetry has provided experimental techniques for characterizing particle track structure in terms of the probability distribution of the stochastic quantity lineal energy, which is based on the energy transferred by a passing particle to a simulated microscopic target volume of typically few µm in size, i.e. in the order of the magnitude of cell nuclei. On the other hand, studies based on detailed numerical simulations of track structures provided evidence that the biologically relevant target size might be in the range of few nanometers where experimental microdosimetric techniques fail to be applicable. This led to the development of nanodosimetry where track structure is characterized in terms of the probability distribution of the number of ionizations produced by a particle track in a target volume of few nm in size. Similar to microdosimetry, the microscopic target is experimentally simulated by an equivalent gas target of macroscopic dimensions and use of theoretical density scaling relations.

Micro- and nanodosimetry provide a pure physical characterization of microscopic track structure based on time and space correlations of the radiation interaction events. This could pave the way for new concepts for quantifying radiation effects in terms of radiation field properties, separating the physical and biological aspects involved in the biological effects of different radiation qualities. The goal would be a novel unified concept of radiation quality based on measurable properties of the particle track structure; its experimental realization and implementation with 'dosimeter standards' and traceable easy-to-use end-user measurement devices.

**Research lines**

In principle, nanodosimetry enables a three-dimensional characterization of the particle track structure including the statistical correlations between different target volumes which may be decisive for biological effects of different radiation qualities. Such a comprehensive characterization of track structure is the prerequisite for an unbiased identification of the biologically relevant target size, which may depend on which biological endpoint is considered. In practice, however, the few existing nanodosimeters developed so far simulate only a single target volume and, as such, of different sizes. Only recently first attempts were made to develop track structure imaging techniques, on the one hand, and to investigate the relation between track-structure characteristics measured with different instruments, on the other. In this context, the establishment of uncertainty budgets for measured nanodosimetric quantities is an important task for the future, where the budget needs to take into account all sources of uncertainty including bias introduced through incomplete collection of the ions produced in the target. Apart from laying the basis for the development of detection systems for practical use, the research on experimental track structure characterization also provides a benchmark for the validation of track structure simulation codes. In the long run, these activities need to be expanded to experimental investigation of radiation interaction with real nanometric objects in the condensed phase, such as, for instance, nano-droplets of DNA or proteins clustered with water molecules or nano-structured solid-state devices.

Deriving estimates of the uncertainty of nanodosimetric characteristics of track structure is also a major need for the computational methods used for numerical simulation of particle tracks. These numerical methods are, in principle, well suited for studying particle track formation and for obtaining the probability distributions for micro- or nanodosimetric quantities. Some codes have been developed for this purpose by different groups. Using track structure simulation, first attempts to investigate correlations between nanodosimetric characteristics for different target volumes along the track and between target volumes of different size have been made. Further steps along this line towards a 'multi-scale' characterization of particle track structure need also to include studying the link between nanodosimetry and microdosimetry. In this context also the relevance of using interaction coefficients with biological molecules (DNA, proteins, etc.) as opposed to water, on whose radiation transport properties most track structure codes are based, needs to be investigated.

Numerical simulation techniques for track structure are mostly based on Monte-Carlo techniques that take into account each individual interaction (step-by-step simulations as opposed to the common condensed-history approaches). Two major concerns have recently been raised against this approach. One is that in this Monte Carlo approach the ionizing particles are basically treated as classical particles for which location and momentum can be defined at the same time. Particularly for electrons with energy below 1 keV, i.e. for the vast majority of electrons produced in ionizing interactions, this is in contradiction to the Heisenberg uncertainty principle. The second challenge is related to the use of the cross section concept in a context where subsequent interactions occur at average distances in the nm range, so that they cannot be considered as independent. Some alternative methods for simulating track structure characteristics without using Monte Carlo techniques have been developed which, however, also rely on albeit effective cross sections.

With respect to the aim of developing measurement devices for track structure properties with the potential for practical applicability, the most advanced developments are miniaturized tissue-equivalent proportional counters and solid-state microdosimeters based on silicon. In addition, also calorimetric microdosimeters are under development whose major potential lies in their capability to measure energy deposition directly in tissue-equivalent material, such as to obtain a means of 'calibration' for the other types of miniaturized microdosimeters. For nanodosimetry, first attempts are in progress to develop measurement devices for track structure that are based on the radiation-induced change in resistance of electrical circuits built from DNA molecules.

### *3.1.2 To quantify correlations between track structure and radiation damage*

**Introduction**

The comprehensive multi-scale characterization of the physical aspects of particle track structure will enable a quantitative investigation of the impact of particle track structure in terms of biological effects at the subcellular and cellular level. To this end, radiobiological experiments and radiobiological modelling need to be included. In order to obtain a quantitative and comprehensive characterization of the correlation between microscopic particle track structure and radiation damage to biological cells, biological cells need to be exposed to single particle tracks. In these radiobiological experiments, information on the geometrical relation between the particle track and the exposed cells is required such as to be able to relate the features of the track to the biological outcome.

Track structure will most likely show a strong correlation with the induction of early biological effects such as the occurrence of single and double strand breaks of the DNA. As later biological endpoints also show a dependence on radiation quality, there should also be a correlation of track structure characteristics and the probability of inducing these later effects, such as chromosomal aberrations or cell death. It is not obvious a priori whether the same characteristics (e.g. probability distribution of the number of ionizations for a particular size of the target volume) will be of relevance for different biological endpoints.

Many radiobiological assays available to date are often dependent on the availability of a large number of exposed cells, as intermediate steps in the applied protocols may have a limited selectivity for the cells of interest. This often leads to outcomes of limited statistical power. Furthermore, for many assays functioning protocols can only be established for a limited choice of cell types, and there is often a strong dependence on the human factor and a number of unknown factors which can jeopardize the success of the assay and appear to be beyond the control of the experimenter. For a high significance of the sought correlation between track structure characteristics and biological effects, an improvement of the dependability of radiobiological assays would be desirable. This would also be beneficial for biodosimetry as a tool for radiological emergencies.

**Research lines**

The method of choice for the purpose of overlaying particle track with biological cells under defined geometrical conditions are microbeams offering targeting capabilities for individual cells

and compartments of cells. Ion microbeams that provide primary particles with pronounced track structure can allow exposure to a controlled number of tracks per cell. Alternatives to ion microbeams are methods based on nuclear track detectors and biological assays that maintain the geometrical relation between cells and tracks.

In these experiments, radiobiological assays are carried out on the irradiated cells to obtain the yield of a particular biological endpoint for a particular radiation quality and a particular geometrical arrangement of the particle track and the irradiated cell. A multi-scale characterization of the physical characteristics of the track structure would also be carried out by using nanodosimeters with multi-scale measurement capabilities or by employing track structure simulation codes that have been benchmarked with nanodosimetric measurements. Statistical cross-analysis would then be carried out to identify, for instance, correlations between the yield of a particular biological endpoint for different radiation qualities and nanodosimetric probability distributions for particular target sizes, such as to identify the most relevant target size for this endpoint.

Depending on the biological endpoint, radiobiological modelling will be involved to a different extent in establishing these correlations. Benchmarking will therefore be essential. This could for instance be achieved by exposing cells to 'equivalent' combinations of particle tracks of different radiation quality. These 'equivalent' combinations could be found using simulations of track structure and would be defined by producing the same combined probability distributions used as track structure characteristics (for the identified 'relevant' target size). The benchmarking would require cells exposed to particle tracks of mixed radiation quality, which would need appropriate irradiation setups to be developed.

The correlation between yields of certain biological endpoints and track structure characteristics would have to be systematically studied for a variety of human cell types of different differentiation and coming from donors of different age and gender such as to obtain information on the presence or absence of age and sex dependent differences as well as on interpersonal variability. The goal would be to find potential weighting functions for track structure characteristics that allow predictions of biological effects based on track structure measurements. This would be a prerequisite for new dosimetric concepts quantifying radiation effects at the level of individual cells or small compartments of tissue. If the sought correlations should predominantly occur for a specific value of target size, nanodosimeters simulating this target size could be used for the realization of these new dosimetric quantities. Otherwise, measurement techniques for their realization would need to be developed from scratch.

### *3.1.3 To improve understanding of biokinetics and dosimetry of internal emitters*

**Introduction**

One of the key issues in internal dosimetry is how information on dosimetry and biokinetics of internal emitters can be used to improve our understanding of radiation-induced effects and mechanisms of effect occurrence.

Low concentrations of incorporated radionuclides are characterized by spatially and temporally inhomogeneous dose distributions within a tissue or organ. The spatial inhomogeneity of target

cells as well as the sensitivities of various cells in a given tissue or organ may result in different health effects. Additionally, the temporal exposure inhomogeneity, that is acute, chronic or fractionated irradiation, and the dynamic behaviour of radionuclide distribution within tissues and organs may affect the biological outcome. Thus, average quantities like average absorbed organ doses may not be appropriate for the estimation of biological effects of low doses. This is partly taken into account by the latest ICRP models which for example consider the inhomogeneous distribution of target tissues in the skeleton and (on a larger scale) of deposited activity in the respiratory tract.

Radiologically important radionuclides in internal dosimetry which may require a microdosimetric approach are alpha and beta emitters, such as isotopes of plutonium and strontium in the skeleton or short-lived radon progenies in the lungs, and Auger emitters, such as iodine isotopes, in the thyroid. For example, in case of inhalation of short-lived radon progeny in the lung, highly localized deposition of alpha-emitting radon and thoron progeny may induce very high doses on a very local (a few hundred micrometer) scale that may even lead to cell killing, although the mean organ absorbed dose to the lung might be quite low.

One of the most important issues in low-dose research is the analysis and characterization of possible thresholds in observed health effects. By decreasing the dose, its role may become negligible compared to the role of confounding factors or compared to the repair mechanisms of cells and tissues. Another consequence of inhomogeneous cellular dose distributions is that modelling of tissue response instead of single cell responses becomes even more important because of interaction among adjacent cells.

Low-dose effects of high and low LET radiation are quite different. High LET radiation reaches only a small number of cells depositing a high amount of energy whilst low LET radiation affects more cells with a smaller amount of energy imparted. Thus, alternative ways of assessing high and low LET exposures should be investigated such as fluence, hit probability and microdosimetric energy distributions. Improving dosimetric quantification can decrease the uncertainty of the dose effect relationships.

**Research lines**

Characterisation of the spatial inhomogeneity of dose and its effects on different scales from individual molecules to the whole body is needed, with a particular focus on the development of calculation tools for alpha microdosimetry. Other scenarios of interest are the deposition of $^{90}Sr$ within femur bone, radon and thoron in the lung, deposition and clearance models for inhaled radon progeny, cellular effects of low doses and low dose rates with the focus on DNA damage and stress response, simulation of microdosimetry in a virtual cell and track-structure-based calculations of initial radiation damage and its effects on the DNA, tissues and organs. This will require the study of deposition of radioactive material on different scales from organelles to the whole body including benchmarking of Monte Carlo codes – from micro to macro dosimetry. At the very end of this line, alternative quantities based on nano- and microdosimetry instead of absorbed dose may be developed to predict health effects.

These efforts must be accompanied by the development of more realistic models of radionuclide deposition in the various regions of the lung than are currently available, describing the energy deposition of incorporated alpha emitters on a micrometer and nanometer scale and estimating

the corresponding local biological effects. The results should be combined with epidemiological observations, for example after residential radon exposure or inhalation of plutonium (occupationally or accidentally). The same approach can be applied to the development of more realistic thyroid models that permit studying deposition of electron and photon emitters in the thyroid after accidental intakes of radioiodine isotopes; this study will focus on public exposures, taking into account a wide range of ages from foetus to adolescents and also adults. This research may even include development of new dose concepts that are described in Chapter 3.1 of this report.

There is increasing evidence that the tissue response after irradiation with high LET radiations may be different from that observed in individual cells, e.g. through the interaction of cells via bystander mechanisms. To extrapolate from effects in single cells, where experimental information is currently available, to biological effects in tissue, which may be related to epidemiological findings, requires research on radiation effects in 3D tissue models, both experimentally and theoretically. In terms of dosimetry, this raises the question, whether currently identified progenitor cells are indeed the primary target cells or whether all surrounding cells may contribute through bystander mechanisms.

For radiation protection purposes, carcinogenesis is the most important radiologically induced health effect at low doses. It is common practice in cancer research to assume a multi-step model, including initiation and promotion mechanisms. Initiation is currently assumed be related to cellular transformation in single cells and thus depends on the local dose. An important promotional factor is inflammation of the irradiated tissue, which is again related to local dose. Hence from a dosimetric point of view this 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. In the case of lung tumors, cigarette smoke is the most important promoting agent, as evidenced by epidemiological studies, whose deposition pattern follows very similar biokinetics as that of inhaled radionuclides.

### *3.1.4 To Update Operational Quantities for External Exposure*

**Introduction**

The protection quantities cannot be physically determined by measurement. In order to answer both social needs and metrology, a quantity, or set of quantities, is required that can be related to the protection quantities for the purpose of the safe control of ionizing radiation and legislative requirements, and can be determined by measurement. The quantities must be: self-evident (obvious); comprehensible to the users (simple); as easy as possible to determine; stable; without ambiguity for defining all the components of the radiation field at a point or at a position on the body; having mathematical properties (additivity, linearity). The role of the operational quantities is to provide a reasonable estimate of the protection quantities for optimization and in assessing compliance with the limits. The operational quantities must be defined, without restriction, for all particles and energies for which the protection quantities are provided.

**Research lines**

The current operational quantities were defined by ICRU. Conversion coefficients for the operational quantities and the protection quantities were published by ICRU and ICRP for photons, neutrons, and electrons.

ICRP has recently published revised formulations of the protection quantities (Publication 103), a standard set of male and female anthropomorphic phantoms (Publication 110), and a set of conversion coefficients for the updated protection quantities (Publication 116). In the new compilation, particle type and energy range of the conversion coefficients are extended compared to earlier publications. The conversion coefficients calculated using full transport of particles, are presented for photons (up to 10 GeV), neutrons (10 GeV), electron/positrons (10 GeV) plus protons (10 GeV), muons (10 GeV), pions (200 GeV) and He ions (100 GeV/nucleon). The extension of particle type and energy range is intended to meet a need for exposures in high-energy particle accelerators, aircraft and space. The operational quantities will be needed for these particles over the whole energy range in order to adapt the new protection quantities to the system of radiation protection. In this context, further consideration is being given to the definitions of the operational quantities: any changes made to the definitions can have an impact on the design of area monitors, personal monitors, and calibration procedures.

As far as operational quantities are concerned, neither $H_p(0.07)$ nor $H'(0.07)$ may provide the best assessment of the stochastic or deterministic effects in skin. Thus, a modified system of operational quantities (addressing for example the control of exposure due to hot particles and other external sources of skin irradiation) is needed.The operational quantities used in radiation protection practice including those mentioned above for skin dose assessment must be capable of being measured with simple monitoring instruments, and they should provide a sufficiently conservative estimate of organ and tissue equivalent doses and effective dose limits. Therefore, it is very important to consider the availability of device and calibration facilities as well as the establishment of calibration procedures to define the operational quantities for new particles and extended energy ranges.

## 3.2 Towards improved radiation risk estimates deduced from epidemiological cohorts

Radiation dosimetry for irradiated humans is important (i) for the treatment, diagnosis and protection of the individual and (ii) for the understanding of the effects of ionising radiation on humans. Current knowledge of relationships between dose and radiocarcinogenic risk, 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 to ionizing radiation, e.g. acutely at the Japanese bombings and some medical exposures, or chronically by radionuclide releases from the Mayak nuclear facilities in the Southern Urals). The basis for all risk estimates is absorbed dose. In order to give maximum support for future 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 which were present for example at work places of nuclear workers, or if there were multiple exposures to ionizing radiation in medical applications (diagnostics and therapy).

Radiation research is performed to quantify the radiation risk involved in a certain exposure situation, in order to judge whether this exposure can be justified or not. In this context the concept of risk coefficients, i.e. the risk of a certain outcome per unit dose, is a central element. In a dose-response curve, the risk coefficient can be interpreted as the slope of the curve which corresponds to the ratio of the risk and the dose, at a given dose. From this it is evident that uncertainties in quantification of the outcome (risk) or uncertainties in quantification of the dose would both contribute to the uncertainty of risk coefficients. In this sense, radiation dosimetry must be considered as an essential foundation of radiation risk estimates. Dosimetry therefore represents an essential input to radio-epidemiological studies, whether in radiotherapy and diagnostic imaging follow-ups, studies on occupational exposure and exposure of the general population, or accidental exposures.

Presently the most important radio-epidemiological cohort is the cohort of atomic bomb survivors from Hiroshima and Nagasaki which has been followed-up by the Radiation Research Effects Foundation (RERF; former ABCC) since 1950. Although considerable efforts have been made since the 1950s to quantify the doses of the survivors included in the so-called Life Span Study (LSS) on an individual level – with the DS02 Dosimetry System being the most advanced of a number of consecutive dosimetry systems – still a number of fundamental open issues have been defined recently.

Other cohorts include populations exposed at the Techa River area from releases of the Mayak nuclear facility, after the Chernobyl accident (thyroid cancer) and more recently after the Fukushima accident. Among occupationally exposed groups, uranium miners, radiation technologists, Chernobyl liquidators, Mayak workers, other nuclear workers, air crew etc. are of concern, while other studies include individuals exposed due to radiotherapy (tinea capitis, hemangioma, breast cancer, thyroid cancer, etc.).

In a few years, follow-up of a number of studies will finish, due to the aging of the involved cohort (e.g., LSS) and consequently other cohorts of irradiated humans may become more and more important in the future, including offspring cohorts of exposed parents. Cohorts such as radiotherapy and diagnostic imaging patient populations, for example, are useful candidates because of the large number of individuals involved, the medium-high doses, and especially because patient doses are well controlled and documented. For this reason, development and harmonization of medical dosimetry is important. Other efforts include the establishment of national cohorts of individuals of the general populations.

In the past, in most cases incidence and/or mortality of various cancer types were of major concern (all solid tumours combined, tumours at certain organs, leukaemia, thyroid cancer, etc.) 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.

In order to improve risk estimates deduced from such cohorts, a number of dosimetric improvements are required:

- Quantification and validation of exposure pathways that have not yet been considered so far for certain cohorts. This includes doses to certain organs and tissues that need specific attention (e.g. eye lens, 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 lung after inhalation of alpha emitters)
- Improvements in techniques of retrospective dosimetry for historical cohorts and validation of the doses estimated (e.g. for Chernobyl liquidators, Techa River populations, LSS, Mayak and Sellafield nuclear workers, uranium miners)
- Improvement of uncertainty evaluation of doses estimated by retrospective dosimetry techniques

For the vision of improved radiation risk estimates deduced from epidemiological cohorts the following challenges were identified:

- To explore exposure pathways not yet considered or validated
- To improve retrospective dosimetry for exposure pathways already considered

These challenges are described in detail in the following.

### *3.2.1 To explore exposure pathways not yet considered or validated*

**Introduction**

While considerable efforts have been made in the past to quantify exposure of individuals in cohorts used to deduce various radiation-induced risks for various endpoints (e.g. solid cancer, non-cancer diseases, chromosome aberrations, cataracts, etc.), we have identified a number of exposure pathways that have not yet been included or validated in dose estimates of relevant radio-epidemiological cohorts. These cohorts include, for example, atomic bomb survivors, aircrew, medical radiotherapy cohorts, Techa River population, and national cohorts of populations currently being established in a number of countries. For the pathways identified the corresponding doses must be quantified in an effort to establish an integrated individual dosimetry to be used for deduction of reliable dose-response curves from epidemiological cohorts.

We also note that for a number of tissues and organs that are important for radio-epidemiological cohorts, exposures cannot adequately be calculated yet. For example, cancer following prenatal exposures, and non-cancer effects induced by ionizing radiation such as cardiovascular diseases, neurological (cognitive) impairments or lens opacities (cataracts) are of increasing concern, and a number of epidemiological studies have already provided some evidence for statistically significant radiation-induced non-cancer effects and cancer risk due to in-utero exposure (e.g., atomic bomb survivors, Mayak workers, Techa River population). For the establishment of reliable dose-response relationships for these endpoints, realistic dose estimates to the organ of concern must be available. Such doses are, however, not yet fully considered in dosimetry and have to be developed.

**Research lines**

Recently, open issues in a-bomb survivor dosimetry of the Life Span Study were discussed and it was felt that exposure from residual radioactivity induced by neutrons in the environment and some internal exposure pathways need still to be addressed. Biodosimetric methods such as EPR on tooth enamel or measurement of stable chromosome aberrations (translocations) in peripheral blood samples of survivors may help to quantify individual exposures. Neutrons are still of some concern and although neutron activation products have recently been successfully measured in tissue samples (enamel) from survivors, calculated fast neutron doses for the Nagasaki cohort still require experimental validation of environmental samples.

In the case of air crew exposed to secondary cosmic radiation during flight, considerable efforts have been made in the past to quantify – mainly by simulations that were validated by measurements – annual effective doses. These efforts showed that in many countries pilots and cabin crew is the cohort with the highest occupational exposure (both in terms of mean annual effective dose and mean annual collective dose). Dose contributions from Solar Particle Events, that may increase the dose rate from secondary radiation in the atmosphere by 1-2 orders of magnitude for several hours, however, have not yet been addressed. Some efforts must be made, in particular with respect to quantification of the energy distributions of primary protons emitted by the Sun during such events and with respect to measurement campaigns onboard aircraft, before reliable dose estimates can be made. This also holds for astronauts in space, and may also be important, for example, for studies on electronic effects (Single Event Upsets) to electronic components used in aviation and space, keeping in mind that highly-engineered modern societies are particularly vulnerable if SPEs affect electronic communication and GPS navigation.

Epidemiological studies of second cancers following radiotherapy must have a specification of dose to the patient. In some studies, however, it has not yet been possible accurately to determine dose to the tissue at the site of the second cancer. By harmonizing out-of-field dosimetry techniques for radiotherapy patients, and dosimetry for various diagnostic procedures, EURADOS can contribute significantly to future epidemiological studies by developing “the complete dose specification” from all sources of radiation (see also section 3.4). This may even include dose contributions calculated on a sub-organ level as described below.

Currently, in a number of countries such as Germany there are efforts to establish national cohorts. These efforts aim to investigate causes of common diseases among the general population such as, among many others, cardiovascular diseases and cancer, quantification of risk factors, and identification of prevention strategies (see e.g. http://www.nationale-kohorte.de/index_en.html for Germany). Due to the large number of individuals included (about 200,000) and the planned length follow-up (10-20 years) such cohorts may also be suitable for the investigation of the role of ionizing radiation in the induction of the various investigated endpoints. A prerequisite is of course reliable dosimetry for the participants. While this will not be possible for all participants, we expect that in these cohorts, sub-groups will be defined for which sophisticated determination of all relevant exposure pathways from natural sources of ionizing radiation (cosmic radiation, terrestrial radiation, radon, internal) will be performed. Methods need to be developed to measure these exposure pathways on an individual level without compromising the daily life of the participants.

Exposure scenarios typical for the population at the Techa River are particularly complicated because they include a combination of external and internal exposures. For an integrated

individual dosimetry of the members of this group, a combination of dosimetric techniques must therefore be applied. Physical dosimetry on environmental samples using TL, and analysis of radionuclide composition in historical water samples as well as historical dose rate measurements in the environment have already been used to validate assumptions on the source terms of the Mayak releases. Biological dosimetry such as fluorescence in situ hybridization (FISH) techniques to identify stable chromosome aberrations and EPR on tooth enamel should be complemented by internal dosimetry techniques (in-vivo and in-vitro bioassay methods) quantifying the dose from incorporated long-lived radionuclides such as 90Sr or plutonium isotopes. The radiation-induced EPR signals result from combined contributions of external exposure and radionuclides incorporated in tooth tissues. Techniques for assessment of the internal dose to tooth tissues and data analysis must be improved to enhance discrimination of external and internal dose components and to separate contributions of natural background radiation and atmospheric radionuclide releases. The effects of radiation may be altered by the presence of confounding factors or of other contaminants or stressors which may be the case when cytogenetic methods of dose reconstruction are used; this will require further analysis.

After the Fukushima accident in Japan, a considerable number of members of the public were exposed to released radioiodine isotopes. EURADOS has been collaborating with the National Institute of Radiological Sciences in Japan (NIRS) since 2012 in a project for the reconstruction of early internal doses in the TEPCO Fukushima Daiichi Nuclear Power Station Accident. For this project, computational dosimetry is used as an alternative tool in internal dosimetry when physical phantoms are not available for in-vivo calibration of whole body counters. Monte Carlo simulations using voxel phantoms permit calculation of counting efficiency of the detectors used for measurements, for different ranges of age of the exposed population, resulting in more accurate calculation of activity of radioiodine deposited in the thyroid. This approach should be implemented to improve the on-going process of reconstruction of doses to workers and the population affected by the Fukushima accident, but can be also applied in other scenarios.

Furthermore it is our vision that during the next decades, models of critical organs such as the heart, the brain or the eye lens with high spatial resolution will become available that allow quantification of absorbed doses in substructures of the organs of interest. This will require development of voxel phantoms of these organs with voxels on a sub-mm size that will allow – in combination with radiation transport calculations in the human body – calculation of absorbed doses from primary and secondary particles in organ sub-structures such as, for example, the arteries of the heart. The final goal of this research will be to establish fluence-to-dose conversion coefficients for organ sub-structures of interest, for relevant radiation types. This research should include organs of various sizes, and in particular organ sizes that are typical for children and young adults (adolescents). The radiation to be studied depends on the exposure scenario of the investigated cohort and may include photons (medical cohorts, e.g. CT exposures), a mixed photon and neutron field (a-bomb survivors), combined photon, proton, neutron, and ion exposure (particle therapy), photons and alpha particles from incorporated alpha-emitters (Mayak workers), beta particles (90Sr in Techa River, radioiodine intakes due to Chernobyl and Fukushima accidents or in radiotherapy patients), or even mixtures of external exposures and internal exposures due to a variety of incorporated radionuclides (Techa River populations, Chernobyl population, uranium miners, nuclear workers).

For any organ of interest, the computational efforts described above should be complemented by development of miniaturized detectors that will allow measurement of doses from various radiation types within small substructures of a suitable phantom, or even within a patient during irradiation (e.g., brachytherapy).

### *3.2.2 To advance retrospective dosimetry for exposure pathways already considered*

**Introduction**

Retrospective dosimetry consists of methods that measure persistent chemical, biological or physical changes, in biological tissues or inert materials, which can be directly related to the absorbed dose of ionizing radiation. In other words, retrospective dosimetry measures markers of exposure which persist long enough to measure doses received weeks or years before sampling. In epidemiological studies, these methods are appealing because they complement conventional dosimetry, such as film badges, when this is not available or reliable, and allow for a dose estimate which is independent of the analytical models. Retrospective dosimetry has indeed helped significantly to validate analytical model-based doses either of environmental samples, or of individuals such as inhabitants of contaminated territories and Mayak and other nuclear workers, in the largest epidemiological studies. In particular, long-lived (i.e. for years) markers of exposure have been valuable tools for dose assessment of historical and chronic cohorts (e.g., survivors in Hiroshima and Nagasaki, inhabitants of the Southern Urals).

The ideal objective is to use retrospective dosimetry for molecular epidemiology, i.e. to provide individual doses having little bias and small random errors, and to permit discrimination between different pathways of exposure (i.e. internal vs. external) and radiation qualities. In our vision, this long term objective can be approached through the following research lines.

**Research lines**

In all the epidemiological studies of historical cohorts, the dose estimates fell mainly in the low-intermediate dose range. Currently, the most consolidated long-lived markers (EPR with teeth, FISH of stable translocations in lymphocytes, TL/OSL in ceramics) have a detection limit in the 25-300 mGy dose range. These levels should be reduced in an effort to reduce the uncertainties at low doses. Markers of exposure with higher sensitivity and lower detection limit than those currently used should also be investigated.

Approaches to both reliably assessing and reducing the uncertainties associated with estimated dose should be explored. Possible ways to do this are: inter-laboratory comparisons and error propagation from the single sources of uncertainty, e.g. by Monte Carlo calculation.

Epidemiological studies of long-term effects are usually carried out between six months and some decades after exposure, so the marker must be stable enough to provide significant dose estimates after this time. EPR of tooth enamel, TL/OSL of ceramics and FISH of stable translocations in lymphocytes are nowadays considered the most reliable markers for dosimetry in cases of radiation exposure that occurred many years ago. Other stable markers should be identified, including those that are suitable for molecular epidemiological studies.

To reduce the bias in retrospective dosimetry, confounding factors should be identified and reduced. Especially, how the effects of radiation are changed when other contaminants or stressors (chemical, biological or others) are present should be studied. Other sources of bias might be age- or gender-dependent. It will be necessary to characterize further the dynamics of lymphocyte homeostasis and circulation within the body and the effect of radiation on these processes.

As a general rule, in epidemiological studies, sampling should be as minimally invasive as possible. In historical cohorts, in some cases, tissues can be collected as they become available over the years, as, for instance, tooth enamel for which large sample banks exist. However, for other tissues, such as blood, storing can affect the quality of samples or the information contained therein. Appropriate sampling and storing methods have therefore to be identified and harmonized.

The number of subjects studied using retrospective dosimetry in epidemiological studies has been relatively small because of the relatively low capacity of measurement and because of the invasive sampling. For instance, one single EPR laboratory can measure, full time, about 150 tooth samples in one month. Possible ways to enlarge the measurable cohort are, in our vision: a) developing faster and minimally invasive techniques, such as *in vivo* EPR on teeth or mini-biopsies techniques in combination with high frequency EPR, b) surveying high throughput biological techniques, c) making techniques easier to perform, field deployable and cheaper (for instance using cheaper reagents), d) considering web scoring of cells, and e) making use of an analysis network consisting of several laboratories working with standardized and harmonized protocols for both, biological sample handling and analysis of biomarkers. The last approach (e) could clearly improve retrospective dosimetry results in molecular epidemiological studies, e.g. long-term follow up of exposed person groups. Such an infrastructure, which could act as a research service network and offer a high cell scoring capacity, is currently being established within the RENEB collaboration.

The improvement of the dosimetry of internal exposure in epidemiological studies is expected to come from the improved realism of updated reference biokinetic and dosimetric models as well as from the collection of information on measurement techniques and on individual exposure. The characteristics of measurement techniques and exposure depend on countries, sites, and time periods in history. The collection of individual specific information on measurement techniques is important in interpreting the available data correctly, especially where they are reported as less than a detection limit. The understanding of exposure is important in the correct application of the dosimetric models by specifying a realistic time course of intake, deposition and absorption rates of radionuclides, depending on the working or living habits and the physicochemical form of the radionuclides.

The measured dose should be easily related to a single organ. This is not always achieved for the currently available methods, especially for internal contamination. Exposures to penetrating external radiation result in fairly uniform irradiation of body tissues, hence similar doses to all tissues, for which FISH and EPR dosimetry can provide a reliable measure of this whole body dose. However, intake of radionuclides by inhalation or ingestion may result in retention in specific organs and tissues, so that the distribution of dose is highly heterogenous. For radionuclides emitting short-range radiations (e.g. alpha particles), this heterogeneity can apply to dose delivery within tissues and between cells within tissues. Work is ongoing in an attempt to address the question of whether FISH provides valid estimates of cumulative red bone marrow radiation doses in cases of incorporation of radionuclides or combined external and internal exposures. To date,

research in this area has been chiefly focused on data from the Mayak and Techa cohorts and by considering evidence regarding the origin and lifetime dynamics of lymphocyte subsets in the human body in relation to the localized delivery of dose from the internal emitters strontium-90 and plutonium-239. Although it is currently accepted that the FISH translocation assay can be usefully applied for detecting internal and combined external gamma and internal doses from internally deposited strontium-90, with fairly large uncertainties, much work remains to be done in terms of establishing and validating dose-response relationships for plutonium-239, as well as other radionuclides. A key component of this work will be establishing the relative biological effectiveness of the different types of radiation, as there is currently a distinct lack of conclusive evidence with regard to formation of stable chromosome aberrations, in the published literature.

A reliable assessment of uncertainty of individual internal doses in epidemiological studies such as that on the Techa River population, or that of the Mayak workers, Russian and UK plutonium workers, European uranium miners and workers, is expected to improve evaluation of any dose response function and of its statistical significance. 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. The uncertainty on the estimated dose is acknowledged to be generally higher than for external exposure, but is usually not evaluated in practice.

Discrimination of acute/chronic exposures, or different radiation quality might be achieved by a multiparametric approach, i.e. merging the results from several retrospective dosimetry techniques. This should be feasible especially for neutrons.

In the short term, retrospective dosimetry will continue to be used for validation of analytical model-based doses in representative groups. However, there is a difficulty in obtaining biosamples from a representative group of persons and there can be a factor of 100 between the number of collected samples and the number of samples to represent a group adequately. Sharing of data and biosample banks within the international scientific community should therefore be encouraged.

Development of new methods and improvement of the existing ones should be tested on a significant number of samples. This is hampered by the difficulty of assessing biosamples for single laboratories. Development and validation of the existing exposure markers have been mainly achieved in the course of large epidemiological studies. Biosample banks should be made available for the purpose of research.

Multiparametric approaches should be also developed to distinguish partial/total body exposure.

As far as Chernobyl dosimetry is concerned, a couple of years ago the FP7 ARCH (Agenda for Research on Chernobyl Health) project was carried out which produced a scientifically sound prioritized list of studies of post-Chernobyl effects in the most relevant cohorts. The studies suggested also the inclusion of some work on dosimetry, although the major foci were medical and biological follow-up studies (http://arch.iarc.fr/). Further validation and retrospective recalibration of historical official dose records could be considered as well as improvement of eye lens beta dosimetry, as a further development of the UACOS (Ukrainian-American Chernobyl Ocular Study) dosimetry. Possibly, some critical review and summary of dosimetric monitoring practices,

retrospective dosimetry efforts and evaluation of radiation protection approaches might be of value as a lesson and recommendation for the future.

Further development of the time-and-motion approach to reconstruct radiation exposures might be of use. This should include elaboration of methods for assessment of uncertainties in the information obtained by interviews of individuals who were exposed some time ago. Development of computer-assisted interview techniques, that include a virtual 3-D representation of the local exposure situation, is also considered helpful, in an effort to facilitate recall of those exposed.

### 3.3 Towards efficient dose assessment in case of radiological emergencies

Radiological emergencies are considered a major challenge of modern societies. These emergencies may include

- incidents that have an impact on large geographical areas (such as the Chernobyl or the Fukushima accident) and lead to exposure of large groups of the general populations,
- terroristic attacks using for example dirty bombs that involve conventional explosives and (allegedly) radioactive material, and
- accidents that involve radiation sources used for example in industry or medicine.

Each of these exposure scenarios is associated with specific problems in determining the radiation doses and the radionuclides involved, identifying individuals who are at highest risk (triage), and deciding the best method to be applied for evacuation, medical treatment and remediation. All this must be considered keeping in mind some loss in infrastructure (disturbed electricity, destroyed roads, problems in transportation and electronic communication, traffic jams, etc.).

In handling such events, many aspects need to be considered which are beyond the scope of the present SRA. These aspects include information strategies, risk communications, evacuation concepts, treatment of radiation injuries, etc. and should be dealt with by networks such as NERIS or – if distribution of radionuclides in urban and other environments are concerned – STAR. A quick, efficient and reliable estimate of doses to affected individuals or groups of individuals involved in such an incident is, however, a prerequisite which must be known before any further decisions can be made by the responsible authorities and decision makers. Dose assessment is complicated because a number of different exposure scenarios might be of concern including internal exposures from incorporated radionuclides or external exposures from various possible sources. Moreover, real-time monitoring data might be scarce and those which are available may rapidly change with time. In order to provide an efficient assessment of potential exposures and doses in a radiological emergency, a number of dosimetric improvements are required, to allow decision makers to initiate the most urgent actions, including those allowing for a) rapid identification of individuals with high risk of developing radiation-induced injuries (external exposure), b) handling of a large number of dosimetric samples in a short time (external exposure), and c) improvement of methods to assess and reduce doses after internal contamination.

For the vision of an efficient dose assessment in case of radiological emergencies the following challenges were identified:

- To identify and characterize new markers of exposure
- To develop strategies and methods to increase measurement capacity

- To quantify doses after accidental internal contamination

These challenges are described in detail in the following section. To meet those challenges, a multidisciplinary approach involving scientists operating in biological, physical and clinical dosimetry is required.

### *3.3.1 To identify and characterize new markers of exposure*

**Introduction**

If a large number of individuals is potentially exposed in a large-scale accident, then it will be of utmost importance to separate the truly exposed from the vast majority of the "worried-well" and to identify those whose exposure is so severe that immediate medical car is needed. This has to be accomplished while taking into account additional, independent information on doses, exposure scenarios (external, internal), time constraints and number of affected individuals involved. An effective triage is important because the available infrastructure or stocked medicine to treat radiation injuries will be limited, and medical care should be first focused on highly-exposed individuals. Realistically, very few or even none of the affected individuals will have worn a radiation dosimeter. Thus, initial dose estimates must be made based on expert judgement and rough calculations, and any means that would provide additional dose information will be helpful.

**Research lines**

Currently efforts are being made towards identification of materials of daily life that could be used as fortuitous dosimeters. These objects could be personal items worn on or close to the human body such as portable electronic devices, chip cards, glass, clothing, shoes, plastics, and precious and semi-precious stones, measureable by EPR, OSL and TL. The same measurement techniques can also be applied to biological materials tooth enamel, bones, finger nails and hairs. Other objects that are not worn by individuals but were exposed at a certain place could also be used to estimate the radiation field during an emergency. These objects may include household salt or sugars, bricks or other domestic or industrial materials. In all these cases, the response of the chosen material to different radiation qualities (alpha, beta, gamma, neutrons) must be investigated, the stability of the radiation-induced signal be quantified, and measurement protocols identified to allow a quick and efficient first determination of the radiation dose involved.

For biological samples, there is a large interest and potential for mobile systems for application in the field. In order to avoid invasive sampling, research on *in vivo* EPR of tooth enamel is focused on development of spectrometers with portable magnets. Different approaches for the *in vivo* EPR measurements are under investigation: continuous wave with low microwave frequency or pulsed with X band microwave. The development of a suitable *in vivo* method using a portable OSL reader supplied with optical fibers for tooth enamel measurements is also of interest. Alternatively, further research on tooth enamel mini-biopsies (2-5 mg) measured by high frequency EPR to minimize the invasive sampling and EPR/TL/OSL analysis of fingernail clippings is also desirable.

While the above includes well established techniques such as TL, OSL, or EPR, investigation of other physically based analysis techniques (pulsed EPR, radioluminescence, cathodoluminescence, ionoluminescence, Raman, Infrared, UV spectroscopy) could widen the range of materials that can

be used as a dosimeter, and offer further options in an efficient dose assessment. On the other hand, OSL offers the unique possibility to expand the range of stimulation and emission wavelengths to possibly identify signals with greater stability and/or sensitivity.

As for genetic techniques, research is currently focused on further development of the use of microarray and quantitative polymerase chain reaction (PCR) technologies, which should enable gene expression assays to produce and validate a reliable signature of human exposure to ionizing radiation in the near future. This signature will probably not allow prediction of a given dose but will rather allow a distinction between exposed and non-exposed individuals, and as such could be helpful in identifying an exposure above a dose threshold, provided that the post-exposure time is within a defined time period.

Immunocytochemical techniques are relatively new, and thus a large amount of work will be required before they can be used as reliable dosimeters. Nevertheless, protein biomarkers such as γ-H2AX, CRP or serum amylases have some advantages over cytogenetics assays. For example, results can be obtained within hours rather than several days after sampling; sample processing and analysis can be optimized and automated for high throughput; non-invasive sampling may be possible (saliva, buccal cells, hair), depending on the marker, and deployable assay formats already exist or are in development. However, a number of issues have to be considered before these techniques can really be used as robust biodosimetric tools: a) as they are not as specific for ionizing radiation as for example the dicentrics assay, confounding factors need to be fully characterized, b) several calibration curves for different post-exposure times and exact timing between exposure and sampling are required, c) in contrast to cytogenetic and DNA damage foci assays, dose response curves for CRP and amylase cannot be performed *ex vivo*; *in vivo* experiments with suitable animal models and validation studies with radiotherapy patients are therefore required but the translation of animal or cancer patient data to the response of 'normal' humans needs to be considered carefully, d) available data suggest a larger variation than seen for the dicentrics assay and finally, e) there is very little known about their response to different radiation qualities.

Computational techniques are quite straightforward in their concept, but their implementation often requires sophisticated solutions, in particular in urban environments. For this reason the automatic direct input of dose rate measurement data into the databases, powerful interpolation and extrapolation algorithms and tools for prediction of doses are the main routes of further development of time-and-motion techniques. In addition, unlike other retrospective dosimetry techniques, computational methods have the potential for conversion into prognosis and optimization tools for planning of post-accident response, finding the safest evacuation/transportation routes, optimization of the activities of responders and public in different ways – i.e. by collective or individual doses, time before withdrawal from radiation hazard zone, etc. Once implemented, this approach would allow provision of retrospective assessment of individual and collective doses and estimation (prediction) of doses at subsequent time intervals

Whatever technique and dosimetric material is used, the following properties are usually indicated as ideally necessary in retrospective dosimetry in an emergency situation: a) specificity to ionizing radiation, b) reproducibility of the measurements, c) a discernible dose range from 0.5 Gy to tens of Gy, d) good signal stability to allow analysis of recent and distant exposures, e) ability to estimate the extent of partial body exposure, f) ability to discriminate between internal and external

exposure, g) well defined dose response relationships for different radiation qualities and dose rates, h) possibility of generating an *in vitro* calibration curve, i) possibility of assessing the uncertainty of the dose estimate, j) low inter-individual variation, k) controllable impact of confounding factors, l) non- or minimally invasive sampling, and m) standardized, rapid (automated if possible) and cheap sample processing and analysis. These characteristics need to be investigated in detail before a material can be considered as suitable to be used as a dosimeter in an emergency situation.

Despite the importance of research, some of these and other radiation markers may not be suitable as stand-alone biodosimeters or physical dosimeters but would work as part of a multi-parametric dosimetry system which produces a dose-dependent signature. This situation will most probably never change despite ongoing research to improve each method because each tool is inherently limited with respect to the above mentioned requirement.

More and more dosimetric applications on smartphones, using the CMOS camera of the smartphone itself or an external detector, are available and can be used very easily by the public. The main advantage of such public applications is that a huge amount of geo-localized data could be potentially available in "real time" and could be very useful, especially in case of large-scale accidents (like Fukushima). Nevertheless, the major disadvantage is that the quality of the data is strongly dependent on the application and the methodology used to do the measurements. So, it is of great importance to establish protocols for validation of doses measured by the public using smartphone applications.

### *3.3.2 To develop strategies and methods to increase measurement capacity*

**Introduction**

In an emergency situation involving many potentially exposed individuals, measurement of a large number of samples may be required that could far exceed the capacity of nearby dosimetric laboratories. This may be due to the fact that the required dosimetric method is not practiced there, the laboratory equipment is limited, the number of available skilled staff members is too low, or problems in infrastructure after the emergency may prevent optimal use of the existing facilities. In general, a solution to this problem is automation of sample preparation and measurement, development of rapid screening methods for radiation exposure, and improved world-wide networking.

**Research lines**

Analysis of dicentric chromosomes and micronuclei is performed in a computer assisted mode. The metaphases are identified, recorded and captured fully automatically while the final step of the analysis (evaluation of metaphase) is performed by eye. This last step could also be fully automated and there is already some experience in some laboratories that should further be broadened. Even then, however, the comparatively slow autocapture of metaphase images limits the throughput to ~75 tests per day per system. More focus should be given to the development of methods for high throughput and cheap measurements – such as gene expression or protein biomarkers. Despite their potentially larger variability, these assays could at least serve as initial triage tools to enable

rapid identification of any critically exposed individuals among hundreds or even thousands of 'worried-well'.

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. Meanwhile the meaning and usage of such an approach is generally accepted and platforms are being developed to disseminate huge numbers of images easily.

Moreover, networking of laboratories has been identified as a very useful approach to get fast and reliable results of dose estimation. Such networks need to be established and their functionality has to be trained and practiced. Major attention has to be given to quality assurance (QA) and quality management (QM), to guarantee operational readiness of the network and its members and reliability of the results produced. In other words, a great potential for workload sharing through national and international networks, such as the RENEB or the WHO BIODOSENET networks, is expected.

The current situation is characterized by a lack of linkage among retrospective (bio and others), clinical/medical, and physical dosimetry. Therefore, closer collaborations between the laboratories involved in these disciplines should be set up. Development of the complementarity of all the different techniques will be required, as worldwide networking efforts lead to a greater need for comparisons between techniques as well as laboratories. Efforts are required to standardize the new methods and develop rigorous statistical analysis methods to enable formal comparisons of techniques. This particular task was, and is currently being addressed through the EU FP7 MULTIBIODOSE collaboration as well as the RENEB collaboration. Availability of techniques in Europe and around the world is also of interest, and current efforts are additionally focused on training and dissemination of information about the different techniques, which is also expected to reduce measurement uncertainties through inter-laboratory comparisons (see also Chapter 4 on Education and Training, and Chapter 5 on Harmonization and Practice).

### *3.3.3 To quantify doses after accidental internal contamination*

**Introduction**

So far, not much work has been done to link internal dosimetry from incorporated radionuclides with biological dosimetry methods. Biological dosimetry is well established and validated for providing dose estimations following external radiation exposures. In contrast, internal exposures are generally regarded as 'difficult' – experienced bio-dosimetrists try to avoid these because interpreting biodosimetry data in such cases is very challenging, and the standard calibration curves generated *in vitro* are often not valid. Less experienced colleagues who are unaware of all the complicating factors frequently provide dose estimates for internal exposure cases, naively assuming that comparison with their standard calibration curves is all that is needed. Additionally, *in vivo* data derived from animals can be misleading because of differences between species in the spatio-temporal dynamics of radionuclide and lymphocyte distributions in tissues. The current method of choice for estimating internal doses is based on biokinetic modelling of radionuclide measurements in urine and faeces.

On other hand, in cases of high level of internal exposure, bioligands or chelators are commonly administered as a treatment after incorporation of radionuclides of high radiotoxicity such as actinides. Decorporation therapy with DTPA (Diethylentriamene pentaacetate) is a treatment applied after incorporation of significant amounts of plutonium or other transuranium elements. Generally, chelating agents disturb the regular human biokinetics by enhancing their excretion. However, the resulting decrease in radiation dose is currently not well understood and difficult to predict. As a consequence of this the assessment of the final dose does not guarantee a reliable result of the actual internal exposure, or an accurate result of the averted dose.

Moreover, in case of an emergency with suspected incorporation of radioactive materials of a large number of individuals, specific emergency bioassay methods may be needed that have not yet been developed. Dose estimation in cases of mixed external and internal exposure presents a particularly complex challenge.

A specific issue of concern is accidental intake of radioiodine. In such cases, different types of detectors may be used for thyroid counting, and exposed individuals of different ages (foetus, infants, children, teenagers, adult males and females) and sizes may need to be measured for dose evaluation. Intakes of, and doses from, radioiodine accumulated in the thyroid can be also assessed using Monte Carlo (MC) simulations combined with patient-based computational phantoms (voxel phantoms, NURBS phantoms).

**Research lines**

In general, areas to be investigated are (i) the definition of reliable biological end-points which are radiation-specific, stable with time and particularly suitable for the case of a chronic exposure with variable dose-rate; (ii) the definition of the proper dosimetric quantity to be compared to the biological end-point (a major deficit of most of the current studies is use of wrong dose indicators, e.g. administered activity). Cases of accidental and occupational internal exposures from literature should be identified for which biological dosimetry has been performed and for which bioassay data (e.g. in-vitro measurement of activity in urine samples) are available and sufficient for reliable physical internal dosimetry. Special models have to be developed for reliable blood dosimetry, to determine the blood dose and to assess how and to what extent this dose is correlated with the information provided by biological assays. At the moment it is difficult to evaluate this correlation correctly because a) calibration curves for biological dosimetry are usually generated using external radiation; and b) it is not clear against which dose (blood dose, marrow dose, or total body dose) the results of the biological assays should be tested. The situation could be clarified by performing investigations with nuclear medicine patients including evaluation of time-activity curves in blood by means of dynamic acquisitions, and simultaneous collection of blood samples at consecutive times for performing the biological assay. From the time-activity curve in blood, the blood dose at different time post-administration can be assessed, and compared to the results of the biological assay. These kinds of experiments should be conducted in cooperation with nuclear medicine departments. They will have the advantage that in this way it will be possible to assess for each patient an individual rather than an average blood dose.

If investigations are performed using different radiopharmaceuticals, it will be possible to investigate if and to what extent radiation type and quality (energy) influence the response of the biological assay. These experiments, combined with the aforementioned literature survey should

enable the assembly of a comprehensive set of *in vivo* human reference data for biodosimetry following radionuclide intake which, in turn, could significantly improve the quality of biological dose estimates for intake and mixed exposure cases. This activity could also be seen as an important contribution to setup and validate dosimetry techniques that are needed for the implementation of point 2.3.3 of the MELODI SRA (individual radiation sensitivity).

For accidental intakes of high radiotoxic radionuclides (alpha emitters like actinides, the beta emitter $^{90}$Sr and others), rapid methods for in-vitro monitoring of these radionuclides must be developed and validated. For other radionuclides this approach may be complemented by in-vivo monitoring. For example, protocols for the determination and/or screening of radioiodine ($^{131}$I, $^{133}$I) in the thyroid in case of a nuclear emergency should be developed and complex intake scenarios (interference of other radionuclides) should also be considered. Additionally, application of available computational phantoms of the thyroid and development of new thyroid voxel phantoms for children of different ages and for adults of different sex, age and size may be useful, based on CT scans provided from hospitals. Validation of MC results will be obtained by proper in-vivo measurements, while development of reference data on thyroid doses to individuals of different ages from measurements using various types of detectors (e.g. Geiger counters) will help responders in public health management. These efforts are expected to help in the reconstruction of thyroid doses of the population exposed after the Fukushima accident in Japan.

In order to understand the reduction of radiation dose from incorporation of plutonium or other actinides after administration of DTPA, a reference biokinetic model for plutonium under DTPA therapy should be developed to improve the reliability of dose assessments for individuals internally exposed (e.g. in Mayak facility and U.S. Uranium and Transuranium Registries (USTUR)). In-vitro studies and targeted animal investigations will be performed to further investigate the mechanisms involving the chelation route due to DTPA administration. The "physiological realism" approach will be considered, integrating more knowledge of the basic physiological processes into the models for radionuclides. The aim here is to provide a more realistic description of the processes behind the metabolic behaviour of the considered radionuclides, and to understand the factors that change their biokinetics. The latter could be used to adapt the model to the individual, therefore sensitivity analysis for identification of the relevant parameters is required, and to find physiological indicators that can be measured in the individual; the results of this study will help the development of more advanced chelating agents. To achieve all these goals, both *in vitro* cell/tissue experiments and animal experiments will be required. In particular, in-vitro studies (e.g. speciation studies with bioligands and chelators) will provide a fundamental understanding of the complex physiological mechanisms behind the biokinetics of decorporation, which can then be implemented in the models to improve them further. This study will contribute to the definition of an operational tool that will be useful and easy to apply in the case of emergency situations.

## 3.4 Towards an integrated personalized dosimetry in medical applications

Modern medicine offers a variety of diagnostic methods and tools that include imaging techniques where the diagnosed individual is not exposed to ionizing radiation, such as ultrasound and magnetic resonance imaging. In contrast, other methods do involve ionizing radiation such as X-ray imaging, CT scans, PET and others. In many European countries, for example, the use of CT scans has continuously increased over the last decade and this trend is expected to continue. As a

result, even if averaged over the whole population of a certain country, medical exposures are largely responsible for exposure from man-made sources of ionizing radiation, and optimization of the received doses is very important.

Additionally, in European countries a considerable fraction of the population will face a cancer diagnosis at a certain time in life, and radiotherapy (using ionizing radiation) represents one of the major methods of treatment. Approximately half of all cancer patients will receive radiotherapy at some point in their illness. A large world-wide population of patients is therefore exposed to high target doses (mainly using photon beams) in a controlled and well-documented way. The distribution of dose within the body following radiotherapy varies considerably with many factors: the size and shape of the patient, the anatomical location of the target volume, the prescribed dose and the type and energy of radiation (photons, electrons, hadrons) and its application (external, internal). In all cases, 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 low dose effects including regions where non-linear mechanisms have been postulated (e.g. bystander effects), through the region defined largely by the Japanese lifespan study, to the further non-linear region at high doses where cell kill and re-population effects are known to occur.

The development of dosimetry techniques and the measurement of doses is an important pre-requisite for advancing this field of study which will need major efforts in the future. As described in chapter 3.2, epidemiological studies of second cancers following radiotherapy require a specification of dose to the patient at the site of the subsequent malignancy, making out-of-field dosimetry an important field of dosimetric development. 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. Finally, some of the sections in this chapter (e.g. sections 3.4.4 and 3.4.5) may have direct links to chapter 3.5 (e.g. section 3.5.3).

For the vision of integrated personalized dosimetry the following challenges were identified:

- To improve out-of-field dosimetry for photon and particle therapy, including the development of analytical models for out-of-field dosimetry calculations
- To improve dosimetry (including the development of 2D and 3D dosimetry techniques) in modern external beam radiotherapy and brachytherapy. This should also include photon and charged particle radiotherapy, including perhaps boron neutron capture therapy (BNCT) and the development of microdosimetric models for incorporated particles
- To optimize dose estimations in interventional radiology
- To establish reliable patient dosimetry in CT examinations

These challenges are described in detail in the following.

### *3.4.1 To establish out-of-field dosimetry for photon and particle therapy*

**Introduction**

In order to estimate and quantify the risk of second cancers that may occur even decades after treatment of the primary tumour, an overall assessment of patient dose is required. However, to gain a complete picture of the out-of-field (i.e. outside the target volume) dose distribution following radiotherapy is not trivial, because it is necessary to estimate and combine the dose contributions from a) the primary beam to regions outside the target volume in the therapeutic beam path, for photons, electrons and hadrons; b) scattered photons from the patient and linear accelerator leakage; c) neutron production at higher photon energies, and for hadron (protons, carbon ions) therapy; and d) imaging exposures used as part of the radiotherapy process (e.g. treatment planning and verification imaging, at diagnostic and therapeutic x-ray energies).

In addition to second cancer risk estimation, out-of-field dosimetry data will be also important for estimating (i) risks of deterministic effects, (ii) foetal doses and risks for radiotherapy patients treated whilst pregnant, (iii) risks of non-cancer stochastic effects (e.g. heart & respiratory disease), (iv) risks of cardiac pacemaker malfunction, and (v) genetic risks.

These data will also be important in the development, testing and validation of analytical models for calculating out-of-field doses. Such models are useful since it is impracticable to measure out-of-field doses under all possible combinations of treatment parameters.

In this context, specific emphasis should be placed on paediatric radiotherapy because (i) risk factors for children and young adults are higher than in later life and (ii) many paediatric treatments have a good prognosis and patients may be expected to live for periods greater than the latent period for expression of a second cancer.

**Research lines**

The strategic goals to be achieved in the next 20 years are a) to develop and harmonize dosimetry techniques for the measurement and estimation of the complete dose specification from all sources (therapeutic and diagnostic) to patients receiving radiotherapy, (b) to develop analytical models for the calculation of doses at any point in the body from all sources of radiation c) to use the complete dose specification as input to risk models for deleterious effects of ionizing radiation, and d) to support future epidemiological studies of second cancer incidence following human exposure to ionizing radiation (see section 3.2) by developing and harmonizing techniques for comprehensive dose measurements over the whole body.

A prerequisite of this challenge is the development and harmonisation of methods for the synthesis of the total out-of-field doses to patients from all sources (therapy & imaging) during radiotherapy, and the estimation of combined risk. This requires strategies to quantify and store patient-relevant doses and to communicate radiation risks to the public and the medical profession. The challenge of integrated patient dosimetry also requires the consideration of potential doses to the patient from radiotherapy imaging procedures. These may include CT scanning, the combination of PET and CT imaging, MV and kV cone beam CT for treatment planning, localisation, verification and image-guided radiotherapy (IGRT). Studies of the

relationship between image information and patient dose in supporting imaging examinations are important, with the final goal of optimising patient doses from imaging procedures.

Modern radiotherapy includes irradiation modalities featuring – among others – photons with energies above 10 MeV, high-energy protons of about 200 MeV and more, and carbon ions with typical energies of several hundred MeV per nucleon. In all these cases, secondary neutrons may be produced in surrounding materials (linear accelerator components and treatment room structures) and within the patient. These neutrons are of particular concern because they are not confined to the target volume (tumour) but are distributed throughout the patient and contribute to the overall patient dose. Precise dose quantification is desired in particular for tumours with good prognosis, as a successful treatment resulting in a long life expectancy will – through aging of the patients – be associated with an increased risk of neutron-induced secondary cancers. It is our vision that novel small-scale detectors for neutrons and photons be developed that could be used to measure the dose distribution – preferably with a spatial resolution that allows deduction of organ doses or sub-organ doses, thus accounting for potential dose variations within an organ – within suitable phantoms irradiated according to typical radiotherapy modalities. Ideally, these dosimeters can be arranged in a phantom as row, matrix or cubic combination for volumetric dose mapping, without significantly disturbing the dose fluence. Given the fact that some of the radiation sources used in radiotherapy are operated in a pulsed mode, and new such sources are currently being developed such as laser-induced proton sources, special attention should be given to the behaviour of these neutron and photon detectors at high dose rates. These dosimeters must be compared and evaluated, and the associated measurement uncertainties quantified. Special attention must be given to the detection of high-energy neutrons (above 20 MeV) which are a typical component of the energy distribution of secondary neutrons produced in proton radiotherapy (see chapter 3.5.3).

These developments must be accompanied by development of a variety of anatomical or semi-anatomical phantoms including water tanks, BOMAB-like phantoms, anthropomorphic phantoms for dosimeter comparisons and clinical simulations, with special emphasis on paediatric phantoms.

Once suitable detectors and phantoms have been developed, measurements of out-of-field doses in photon and particle radiotherapy based on the simulation of clinical treatments need to be performed. It is anticipated that these measurements would form part of a pan- European project in which many radiotherapy centres would participate, sharing expertise and equipment, and progressing towards harmonisation of out-of-field dosimetry techniques.

It is apparent that detector and phantom developments need to be complemented by simulation of the complex mixed fields of photons, protons and neutrons that is used in these treatment modalities. This includes simulation of the primary particle field produced by various medical accelerators, and interaction of this field with the patient and the materials present in the therapy room. The final goal should be calculations of energy distributions of all particles that contribute significantly to patient dose. This is particularly important for proton and heavy ion radiotherapy where again particular emphasis must be placed on particles with energies above 20 MeV, and currently open questions at those high energies such as missing cross sections, production of secondary particles, validation of Monte Carlo transport codes, nuclear reaction models, etc. need to be investigated in detail.

The results of extensive measurement campaigns, performed using optimized dosimeters and phantoms for currently used radiotherapy beams, verified and extended by Monte Carlo radiation transport calculation, should become available in a dedicated database. An ultimate goal of this research is to develop a set of analytical algorithms for calculation of photon and neutron doses, which can easily be incorporated into modern Treatment Planning Systems (TPS) used in radiation oncology. These analytical functions implemented into TPS would enable the calculation of a complete map of doses for each patient which could be used to assess doses in future epidemiological studies or even, in some special cases, for optimization of radiation therapy of young patients.

Both development of devices for detection of neutrons above 20 MeV and simulation of detector responses and patient doses require reference fields for quasi-monoenergetic high-energy neutrons where these devices and simulations can be benchmarked. We note that in the very near future, it is most likely that in Europe such a facility will no longer be available.

### *3.4.2 To improve dosimetry in modern external beam radiotherapy*

**Introduction**

Radiation therapy plays a major role in treating about half the number of cancer patients. It is very important to be able to measure the dose distribution given to the tumor, in an effort to check if this agrees with the treatment plan. However, *in vivo* dosimetry during external beam therapy could benefit from the development of improved dosimetry techniques. Next to this, the rapid development in new radiotherapy techniques (flattening filter free (FFF) fields, volumetric arc therapy, small fields, proton and heavy ion therapy, microdosimeric characterization for hadrons, etc.) requires a continuous effort in dosimetry research, not only to develop on-line dosimetry techniques, but also to improve calibration techniques.

**Research lines**

Novel dosimeters (boron doped diamond detectors, liquid-IC, scintillator, luminescent techniques, etc.) should be developed, which can be arranged within a phantom as row, matrix or cubic combination for volumetric dose mapping, without disturbing the dose fluence, and which can be used for *in-vivo* dosimetry. In this context, development of smaller and more accurate electrometers, capable of working without cables would also be useful. Further, rapidly developing techniques of 2D and 3D dosimetry which use extended dosimeters such as polymer gels, capable of millimeter resolution, should also be developed and applied to volumetric dose mapping.

Improving the dosimetric performance for special radiotherapy techniques such as flattening filter free (FFF) fields, volumetric arc therapy, small fields, proton and heavy ion therapy, microdosimeric characterization for hadrons is also required

### 3.4.3 To include internal microdosimetry in radiotherapy and medical imaging

**Introduction**

X-rays and radiopharmaceuticals have been used in medical imaging and radiotherapy, respectively, to diagnose and to treat cancer and disease for human health care. The unique features of cellular and molecular radiobiological effects depend strongly on the spatial and temporal distributions of initial physical tracks, on induced chemical radicals and later on dynamical molecular biological progresses. Risk assessment after application of alpha- and Auger-emitters and beta radiations in radiotherapy requires knowledge of the fundamental pattern of the inhomogeneous absorption of radiation energy in organs and tissues at the molecular and cellular levels. In additional to the conventional average organ dose approach, modern approaches of microdosimetry and nanodosimetry represent powerful tools to describe the stochastic nature of the energy depositions and the induction of radicals, and to characterize the health and biological effects of internal emitters.

The analysis of radiation covers – as a first approach – alpha- and Auger-emitters and beta radiation. The analyses will include levels of molecule, cell, tissue, organ and organism. Several types of methods will be applied: *in-vivo* experiments, animal experiments, application of epidemiological data, computational modelling and integrated approaches. Furthermore, the potential application of gold nanoparticles in medical diagnostic imaging and radiotherapy will be investigated. Molecular biological experimental and theoretical Monte Carlo simulation studies 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 microdosimetric and nanometer scale doses of these emitters.

**Research lines**

The local radiation dose at the molecular level of the Auger-emitter $^{125}$I needs to be simulated. The experimental investigations described in the literature on DNA damage and cell survival and cell killing of cancer cells incorporated with $^{125}$I should be used to indicate the possibility of applying $^{125}$I in genetic radiotherapy.

To investigate the potential application of nanoparticles in radiotherapy, Monte Carlo programs may be used to simulate the interactions between the gold nanoparticles and x-rays. In these simulations, the geometry of the cells can be assumed spherical and/or ellipsoidal, and different concentration distributions and sizes of the gold nanoparticles in and around the cells must be tested. The simulations can be complemented by experiments where cancer cells coupled with and without nanoparticles are exposed to x-rays of various energies. The physical interactions between x-rays and secondary electrons with soft tissues and gold nanoparticles should be followed.

We expect spectral CT medical imaging with gold nanoparticles as a contrast agent to be investigated with Monte Carlo methods in an effort to identify the smallest percentage of gold nanoparticles needed to be used as a CT contrast agent in humans. The quantity of gold nanoparticles which is specifically targeted to malignant tissues can be investigated with cell culture experiments as well. The tumor specific monoclonal antibody cmHsp70.1 could be

conjugated to gold nanoparticles with a diameter of 50 nm, and the actual location of the gold nanoparticles in and around the cells be visualized by transmission electron microscopy (TEM).

The medical internal radiation dose (MIRD) committee provides some of the necessary tools that will allow estimation of the absorbed dose at the cellular level. These tools take the form of cellular S-values (absorbed dose per unit cumulated activity). S-values can be used to calculate the radiation dose received by a target region when the radioactivity is distributed in a source region. S-values can be calculated by using Monte Carlo codes.

Knowledge of the spatial distribution of energy deposition in cellular and subcellular structures is important for understanding the biological effects of radiation. Such information is crucial with regard to developing new pharmaceuticals for cancer therapy and to choosing the suitable labelling radionuclide. For modelling the distribution of a local energy deposit as well as radiation effects, Monte Carlo track-structure codes can be used for simulating event by event the slowing-down process of all generations of particles.

### *3.4.4 To optimize dose estimations in interventional radiology*

**Introduction**

The dose to patients in interventional procedures can be high, leading even to deterministic effects. Thus, an improved system of dose calculation and dose monitoring in interventional radiology (IR) for adult and paediatric patients needs to be developed. This would enable assessment and improved use of diagnostic reference levels (DRLs), achievable dose levels (ADLs) and skin dose alert (trigger) levels for optimization of patient doses, improved accuracy of skin and other organ doses, and improved accuracy of population dose estimation.

If this vision is realized, patient-specific real time dose mapping of skin dose, other organ doses, effective doses and practical dose quantities (Dose Area Product (DAP), Cumulative Air Kerma (CK)) will be possible, with known uncertainty and with efficient use of DICOM information. Thus, based on DRL and ADL values, 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 patient doses and radiation-induced risks, and to prevent accidents.

**Research lines**

Practical methods of skin dose measurement need to be developed and tested (using large area detectors, TLD methods and advanced detectors) and the related uncertainties in skin dose measurements and dose mapping need to be evaluated. New systems of automatic dose mapping tools, based on DICOM information, are becoming available in modern equipment. These should be applied, tested and calibrated.

Determination of, and recommendations on, skin dose alert (trigger) levels are still needed, including the investigation of the correlation between skin dose and dosimetric indicators for several IR procedures, including paediatric IR. This will require collaboration with industry and standardization bodies, in order to implement the concept of dose alert for daily use.

DRLs and ADLs for different levels of complexity of IR procedures need to be defined and measured, as well as an improved methodology on their determination and requirements on statistics. Studying the feasibility of using continuous DRL-curves with the possibility of introducing different levels of complexity in accordance with achievable values can be done.

A similar concept to DRLs for patients should be developed for equipment used in IR procedures. For this purpose it is necessary to collect and to compare equipment dose rates for different IR procedures, establish calibration procedures for dose measuring devices, and to organise intercomparisons between clinics involved in such procedures.

Ideally, online patient dosimetry in different imaging modalities should become available. This will require adequate dosimetric quantities for fluoroscopy, computed tomography, cone beam CT and hybrid imaging. In collaboration with industry, improved dosimetric information must be identified that should be provided by future x-ray units for different imaging modalities. Also the possibilities of keeping dose records of patients should be improved through collaboration with the industry. Following online patient dosimetry all the relevant dosimetric quantities and risk evaluators (like effective dose and organ doses) should become available automatically; this will need calibration and testing.

### *3.4.5 To establish reliable patient dosimetry in CT examinations*

**Introduction**

For CT examinations it is important to develop systems of dose monitoring and scanner calibration (with known uncertainties) in order to provide easy use of DRLs, improved optimization of patient doses, improved accuracy of organ dose determination for risk estimations and improved accuracy of population dose estimation. The focus should always be put on paediatric patients.

**Research lines**

Automatic dose mapping systems should be developed. The research line to be followed will include definition of the parameters of interest for dose mapping, analysis of commercially available and individually developed systems, and evaluation of the feasibility of using automatic systems that allow collection of patient dose data on a regional or national scale, in particular for the establishment of DRLs and the estimation of population dose. Harmonisation is a key feature that should allow – in collaboration with industry and standardization organizations – promotion of the practical implementation of these automatic systems.

Harmonisation is also important because there are currently different approaches for patient dose determination and scanner calibration (International Electrotechnical Commission (IEC), American Association of Physicists in Medicine (AAPM), ICRU). These approaches must be tested (e.g. the IEC pragmatic approach with different size of detectors) and compared, and their feasibility for clinical implementation must be investigated. In particular, the impact of applying these approaches for the determination and use of DRLs must be studied and the added value of using dose estimates that depend on patient size (Size-Specific Dose Estimates – SSDE) must be quantified.

Another field of improvement concerns the use of phantoms for scanner calibration and QA measurements in clinical practice, in particular for modern cone beam CT where the use of flat panel detectors poses some dosimetric problems. There are various phantoms proposed and used, and these need to be tested and compared in clinical practice (e.g., ICRU phantom). In particular, with respect to feasibility and practicability, the use of only single-size phantoms requires investigation, and the aspect of using phantoms to evaluate image quality vs. dose should be addressed. Finally – again in collaboration with industry and standardization organizations – the most promising phantoms must be identified, produced, and widely distributed.

In an effort towards personalized dosimetry, methods of patient dose determination should cope with varying patient sizes (e.g. the approach proposed by the AAPM). This needs investigation of the optimum parameters for size specification of patients, tests of the use of SSDE as a DRL quantity in various CT examinations and the possible added value to the Computed Tomography Dose Index (CTDI), studies of the use of the product of SSDE and scanning length as a DRL quantity in various CT examinations and the possible added value to Dose Length Product (DLP). Again, particular emphasis should be placed here on the determination of DRLs for paediatric examinations. Appropriate and practical quantities that can be used for patient dosimetry in CT, and that can take into account the fast evolution in CT modalities, should be developed.

It is our vision that in the end, patient-specific conversion factors from SSDE to organ doses should be available for risk estimations and population dose estimation. This may be achieved by means of Monte Carlo calculations for SSDE and organ doses in various CT examinations for a range of patient sizes, complemented by an experimental determination of SSDE and organ doses for a few cases, to verify the MC calculations. This can include the development of individualized voxel phantoms of patients from CT images in real-time. Such organ doses can help in epidemiological studies of radiosensitive organs, such as eye lens and cataract development, or for the heart to investigate cardiovascular effects.

## 3.5 Towards improved radiation protection of workers and the public

Much research and technical development in radiation protection dosimetry for workers and the public has been carried out, to a large extent within projects funded by the EC. The results of these developments have been transferred to operational radiation protection, including guidelines and technical recommendations. Despite of these efforts, a couple of areas exist in which the status is unsatisfactory, necessitating further research. For the vision of an improved radiation protection of workers and the public the following challenges were identified:

- To improve, validate and implement new biokinetic models
- To develop accurate and on-line personal dosimetry for workers
- To improve neutron dosimetry techniques
- To include nuclide-specific information in environmental monitoring

These challenges are described in detail in the following.

### *3.5.1 To refine, validate and implement new biokinetic models*

**Introduction**

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. The resulting overall uncertainty in the estimated internal dose is acknowledged to be generally higher than that for external irradiation, but is usually not evaluated in practice. Thus, in a very general sense, improvements in internal dosimetry are needed, with potential benefits in radio-epidemiology (see also chapter 3.2), diagnostic and therapeutic nuclear medicine, and radiation protection of workers and the public. In this context, the availability of databases including autopsy cases should be acknowledged and used to validate any developed new biokinetic model.

**Research line**

It is intended to implement the latest biokinetic models which will be published in the new ICRP documents on Occupational Intake of Radionuclides (OIR). These new models are very complex and difficult to apply in individual dose assessment. A EURADOS report should be written with recommendations and guidance on how to use these complex ICRP models for individual dose assessment. The reason for this task is to be able to obtain the most realistic individual dose assessment not only for monitoring purposes but also as a fundamental basis for research on dose response relationships.

The assessment of the effects on internal dose of using sex-dependent biokinetic parameters must be considered as well as the implementation of the new OIR systemic models, including quality assurance of the model results and model formulation. In this context, the National Council on Radiation Protection and Measurements (NCRP) Wound model requires validation with human data, using real cases from databases of the EU-funded project IDEAS and from USTUR (United States Transuranium and Uranium Registries).

While biokinetic models for workers and members of the public used for radiation protection purposes consider the biokinetic behaviour of radionuclides in healthy reference persons, radiopharmaceuticals are administered to patients who may suffer from diseases which might change the biokinetic behaviour of the radiopharmaceutical. Currently, dose assessment is done based on state-of-the-art biokinetic models used in radiation protection. It is obvious, however, that in nuclear medicine therapy, individual dose assessment is essential rather than doses to reference persons and consequently, biokinetic models that take into account the influence of certain diseases need to be developed.

An additional aspect also deserves attention when biokinetic models are used for dose assessment of patients after application of radiopharmaceuticals: because of the short half-lives of radioisotopes used in nuclear medicine, a more realistic modelling of blood retention and urinary bladder voiding is needed. For radiopharmaceuticals which are secreted into the gastro-intestinal tract, consideration of the secretion pathway via the gall bladder may also be relevant, together with a gall bladder voiding model.

The reliable assessment of uncertainties in individual doses would enable epidemiological studies of internal exposure to radionuclides to improve the evaluation of the dose response function and its statistical significance.

### *3.5.2 To develop calibration procedures for partial body counters*

**Introduction**

Dose assessment of individuals with internal contamination is subject to uncertainty due to many factors. Retrospective dose assessment is based on in-vitro and in-vivo measurements. In vivo measurements represent a highly valuable method since they provide actual information on radionuclide activity within the body of an individual. It has many beneficial aspects, but requires a detection system to be properly calibrated in order to obtain quantitative and accurate results. Calibration is usually performed by an object (physical phantom) which resembles as closely as possible the anatomy of the human body or one of its parts. There is no standard procedure to calibrate a partial body counter, and anthropomorphic phantom(s) such as those used in order to assess the skeletal activity of bone seeking radionuclides (e.g., plutonium and americium isotopes) are scarce. Skeletal activities are usually assessed from measurement positions at the knee, elbow or skull. It important to note that calibration based on available skull phantoms, for example, may differ by a factor of two. This is partially caused by individual body parameters such as head size, and by properties of different phantoms (e.g., differences in the construction or activity distribution).

**Research line**

It is intend to develop and implement standard physical and mathematical phantoms and procedures for calibration of partial body counters. Newly developed physical phantoms should improve currently available phantoms and provide a reliable base for general calibration. These phantoms should be complemented by their mathematical representation (voxel, mesh, non-

uniform rational basis spline (NURBS) phantoms), in order to account for individual variability of the persons to be measured.

Improved and standardized calibration procedures will be beneficial for two reasons. Firstly they will directly reduce the uncertainty of the measurement and thus affect final dose assessment. Secondly, more accurate and unified data will provide a better basis for design and improvement of anthropomorphic models.

### *3.5.3 To develop accurate and on-line personal dosimetry for workers*

**Introduction**

The challenge is to provide reliable, accurate and on-line personal dosimetry for occupationally exposed workers. This requires monitoring the workers in real time for all limiting quantities (whole body, eye lens, extremities, brain, heart), regardless of the protection methods used, and to provide input for the optimal application of the ALARA principle. Dosimetric research for personal dosimetry should deliver good characterized active and passive dosimeters for all relevant dosimetric quantities, and good computational tools using advanced tracking technology.

**Research lines**

Active dosimeters need to be developed for all radiation fields relevant for occupational exposure. Many devices exist already, but they are not suited for all of these fields. These active dosimeters should be developed in a way that they can also be used for official dose records. For fields that are used in medical applications and in particular for pulsed fields, improvements are still needed, and for example the dependence of active dosimeter response on dose rate must be investigated. Besides that, all existing devices must be tested for all relevant fields in which they are used. Active dosimeters should also be developed for eye lenses and extremities. Improvement of active dosimeters is also needed so that the measured dose is visible to the operator on-line and that the results can be easily implemented in advanced staff databases.

There is still quite some work on eye lens dosimetry to be done. For example formalisms to measure eye lens doses, to develop practical eye lens dosimeters, and to test and compare different eye lens dosimeters are needed. There is also a lack of data for eye lens doses of workers in different fields such as those present in medical applications, where correlations of eye lens doses with other dose quantities, determination of reference eye lens doses for different procedures, and testing and improvement of the efficiency of different protection measures like lead glasses need to be explored. Particularly, the development of a dosimetry protocol to assess eye lens doses when protective eye glasses are used is urgent. However, the reduction in the dose limit for the lens of the eye to make it equal to the whole body dose limit makes it potentially the limiting quantity in any field where the dominant direction of radiation is from the front, even for fields for which neutrons contribute a significant component of absorbed dose. There is hence an urgent need to assess where eye lens doses are limiting across the breadth of industries where radiation protection is required.

There is also still a lack of practical and reliable extremity dosimetry. Therefore, development of practical extremity dosimeters are called for, to test and compare different extremity dosimeters, to

explore correlations with other dosimetric quantities, and to improve dosimetry in mixed beta/gamma fields, especially low-energy beta fields.

In the medical field, there is the special problem of whole body dosimetry in case of lead shielding (lead apron, thyroid shield). This requires determination of the best algorithm for double dosimetry and development of the best method to monitor effective doses in case of inhomogeneous irradiation (which is typically the case when a lead apron is used).

In the future, the inclusion of dosimetry of other potentially radiosensitive organs (brain, heart) might also be needed. Dependent on the outcome of biological research on brain and cardiovascular risk, for example, doses to these organs might need to be determined.

### *3.5.4 To develop neutron dosimetry techniques further*

**Introduction**

Neutron sources are intentionally used and/or incidentally created in various scientific areas and technical applications (e.g. electricity generation, radiography and tomography, materials research, activation analysis, fundamental research, military activities, production of radioisotopes/radiopharmaceuticals). Some of the fields represent new challenges due to strongly pulsed radiation or very high energy ranges, i.e. radiation fields around high-energy particle accelerators and at flights at high altitudes or space missions.

On the other hand, external dosimetry for neutron radiation, which is inevitably accompanied by a photon component, still presents challenges despite many years of development of neutron personal dosimeters. Neutron dosimetry is still a very challenging task as neutrons are present in mixed-fields, they are indirectly ionizing particles and pose more problems for their detection than other types of radiation. Their energy may cover extremely large energy ranges from 9 (nuclear industry) to 12 (particle accelerators, flight altitudes) orders of magnitude, and their "quality" and subsequently their conversion coefficients from fluence to dose varies by a factor of 50 over the entire energy range. At certain work areas neutrons can dominate the total dose received. However, the higher detection threshold of neutron personal dosimeters can lead to underestimation of the collective dose received from neutrons: this detection threshold remains one of the main deficiencies of neutron personal dosimetry relative to that for photons.

The accuracy required for routine neutron dosimetry is not at the same level as for photon radiation in most workplaces, though this is not always true. Previous studies carried out have clearly shown that responses of personal neutron dosimeters in various workplace fields in the nuclear industry can show over- and under- responses of up to an order of magnitude. Therefore workplace monitoring is a prerequisite to achieve sufficient accuracy, i.e. by evaluating a spectrum correction factor to be applied.

Whilst neutron dosimetry concerns a relatively small fraction of all exposed workers and the usual neutron $H_p(10)$ contribution is often small compared with the dose limit; for some workers, such as air crew, it can be a significant component of total dose equivalent; it cannot be disregarded and reliable dosimetry with higher accuracy should be pursued.

**Research lines**

Improvements of the existing dosimeters are required not only through improvements of existing techniques and/or development of new ones but also through the development of reference radiation fields to determine their response. Unfortunately, the actual reference radiation fields do not cover the required overall ranges in energy and angles encountered in the workplace. Because a facility that provides suitable neutron reference fields is extremely expensive and challenging, a European effort to develop and realize improved neutron testing and calibration facilities is the best way to achieve overall better results.

Furthermore there is a need to characterize simulated workplace fields at a reference laboratory and radiation fields at the working area in terms of personal dose equivalent $H_p(d)$. Workplace monitoring is well-established, and is performed mainly with multi-sphere spectrometers or simply by area monitors, both of which do not provide information on the directional distribution of neutrons. Therefore the results obtained are not sufficient to determine personal dose equivalent. The simultaneous measurement of energy and directional distributions is still a matter for research.

Calibration of neutron personal dosimeters requires specific attention. In standard laboratories it is not possible to reproduce the variety of conditions (mixed-fields and wide energy and angle of incidence ranges) in which dosimeters are then used in workplace fields. Essential tools to guide a development in neutron dosimetry are regular intercomparisons either in standard laboratories or "in-field" conditions. Such intercomparisons are usually not achievable in only one country and therefore European efforts in designing and planning such testing sessions are needed (see chapter 5).

There are specific needs for calibration of detectors and instruments in high-energy and pulsed neutron fields. Currently, reference high-energy fields are strongly dependent on simulation tools, with the measurements themselves being dependent on those same simulation tools for calibration. There is the additional problem of under-reading by active detectors in pulsed fields. Research is required into the appropriate dose rates for high energy and pulsed neutron fields.

### *3.5.5 To include nuclide-specific information in environmental monitoring*

**Introduction**

In March 2011, the nuclear power plant accident in Fukushima Daiichi demonstrated the indispensable need for permanent and reliable environmental radiation monitoring. At present, in Europe more than 5,000 stations allow radiological monitoring data to become available in nearly real-time. In case of a nuclear emergency, national dose rate data have to be provided to the European Commission (EC) on an hourly basis, via the European Radiological Data Exchange Platform (EURDEP). Based on these and other radiologically relevant data, the EC, which is in charge of the European Community Urgent Radiological Information Exchange System (ECURIE) may issue recommendations to the EU member states which could affect millions of people and may have severe economic and sociological consequences.

Currently most dosimetry network stations in Europe are equipped with conventional dosimetry detector systems, which do not provide any nuclide-specific information. However, in case of a

major radiological emergency, in addition to reliable data of dose rates values, nuclide-specific information and data on ground and air contamination levels are of key importance for adequate governmental decisions, and first efforts are currently being made (e.g. in Finland and Germany) to improve the situation.

**Research lines**

In order to improve environmental radiation monitoring in Europe, we expect novel and improved instrumentation for field-station use to 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 such as NaI(Tl), $LaBr_3$, or Cd-Zn-Te, which are in principle all well suited for this purpose, require comprehensive scientific investigations of detector features, spectra evaluation, and deconvolution methods, in order to fulfil today's QA standards. These spectrometry systems could become the core instrumentation of the next generation of environmental radiation monitoring networks in Europe. They could also be used – through measured in-situ gamma spectra – to validate Monte Carlo simulations of dose rate and contamination levels.

In a complementary effort, the use of passive dosimetry systems should also be explored for environmental radiation monitoring, and their advantages and disadvantages systematically discussed and compared with existing and other newly developed systems.

## 3.6 Concluding remarks – the role of computational methods in dosimetry

In many of the areas of research described above, computational methods play an important role. The domain of computational physics is not solely reliant on the Monte Carlo method, but also incorporates deterministic methods that attempt to solve the Boltzmann transport equation, and unfolding methods used to derive neutron energy distributions from experimental data. These other methods are important and should not be overlooked, but the availability of modern codes and powerful computers has made the Monte Carlo method dominant in radiation protection and dosimetry. Important areas of research where computational methods are needed also include representations of the human body at the macroscopic, microscopic and nanometric level. To give another example, the operational quantities used in radiation protection are defined in a manner that only permits their values to be calculated via Monte Carlo calculations. This is equally true for the protection quantities, which are defined in voxelized phantoms that cannot be constructed physically but must be simulated. The availability of Monte Carlo methods has allowed this system of radiation protection to be developed, which makes it an integral part of the field. Consequently, computational methods play a crucial role in most of the radiation protection fields where further research is needed.

# 4 Training and Education

Education and training (E&T) has always been a key issue in EURADOS activities. For example, EURADOS Working Groups often allow attendance of corresponding members or observers in order to offer the chance to scientists, especially young scientists, who can listen to scientific discussions and be updated on the actual scientific programmes, thus allowing their participation in the future. In addition, EURADOS regularly organises specific training events like training courses, winter schools and scientific symposia.

As for training courses, they usually last 3 to 5 days, with limited participation to about 40 attendees and they are related to specific topics in the field of the EURADOS Working Groups. In the past, some of the training courses had two or more editions and were slightly updated if necessary, according to the demand. EURADOS *Winter Schools* have taken place at EURADOS Annual meetings since 2007. They usually last one or half a day and they provide "refresher courses" on topics relevant to radiation dosimetry. In contrast, scientific symposia also organized at EURADOS Annual Meetings, are usually related to research topics or results from EURADOS Working Groups or related research projects. Proceedings of the symposia have been published in peer-reviewed journals.

EURADOS E&T 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 E&T efforts of other platforms is recommended, in order to guarantee efficient use of techniques in dosimetry in all relevant research disciplines where exposure quantification is needed.

As an additional aspect, experience after the Chernobyl and Fukushima accidents demonstrated that much fear among the population arose from lack of information about what radiation is and what "dose" means. It is thus believed that a constantly improved education of the general public and especially of key figures (physicians, physics teachers, journalists) is needed, aiming at a better understanding of ionizing radiation and radiation dose, as well as development of emergency programs to educate and train a large number of people (especially journalists, representatives of local authorities, etc) about technical terms involving radiation and dose.

## 4.1 Implementation of EC directives and technical recommendations into practice

Recently EURADOS has prepared training courses 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, with 41 attendees from Europe and Japan. Among others, the course was very instrumental in defining the future strategy needed for a better harmonisation of dosimetric practice: Participants in the WG02 training course have identified 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.

Future training actions in this field will be based on this experience and on the input by the individual monitoring service (IMS) community. It is desirable that IMSs will regularly attend the

EURADOS Annual Meetings and discuss issues of common interest. On the other hand, the analysis of QA/QC surveys organized on a regular basis is a means of identifying topics where training actions might be needed and welcomed by IMSs. To meet the request of attendants to the 2012 training course the 2013 version had more emphasis on the practical implementation of EN/ISO/IEC 17025 as requested. Further planning of training courses should be linked to the needs of the IMS community.

## 4.2 Training courses on novel or improved dosimetric methods

EURADOS continues to organize a number of training activities, in order to maintain competence in the field of dosimetry. Past training courses included were “Methods in Radiation Measurement”, “Internal Dosimetry”, “Use of MCNP in Radiation Protection and Dosimetry”, “Voxel Phantom Development and Implementation for Radiation Physics Calculations”, etc. (see Appendix for more details).

In case of internal exposures, training for 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 and NCRP Models and Reports.

Other activities that were carried out and which need to be continued in the future include training on upcoming new dosimetric techniques such as, for example, EPR/OSL and TL dosimetry.

## 4.3 Winter schools, workshops and scientific symposia

In the past, Winter Schools were held on the general topics of "Relative Biological Effectiveness, radiation weighting factor and quality factor: their role in quantifying effectiveness of ionizing radiation" (AM2014), “Status and Future Perspectives of Computational Micro- and Nanodosimetry” (AM2012), “Radiation Protection for Medical Staff” (AM2011), “Radiological Emergencies – Internal exposures” (AM2010), “Low-Dose Radiation Effects” (AM2009), “Retrospective Dosimetry” (AM2008), and “Uncertainties in Radiation Dosimetry” (AM2007). These efforts will continue in the future, on general topics which are thought to be important for the EURADOS community.

Scientific workshops and symposia have been organized in the past on actual research topics where EURADOS Working Groups are involved. Typically, proceedings of these workshops are published in peer-reviewed journals. The following topics were addressed in the past: “Dosimetry for second cancer risk estimation in radiotherapy” (AM2012), “Accelerator radiation protection and shielding” (AM2010), “Cosmic Radiation and Aircrew Exposure” (AM2009), “Dosimetric Issues in the Medical Use of Ionizing Radiation” (AM2008), “Characterization of Workplaces for the Assessment of the Doses to Individuals” (AM2007), “Uncertainties in Dosimetry – Principles Through to Practice” (AM2006), “Radiation Protection Dosimetry and Dosimetry for Medical Applications” (AM2005), and “Biological and Physical Dosimetry for Radiation Protection” (AM2004) (see Appendix for more details). These actions will also continue in an effort to present new research findings that were gained from various EURADOS WG actions.

# 5 Harmonisation and Practice

The goal of harmonisation of dosimetric procedures in Europe is central to the overall EURADOS vision. It is obvious that every strategic objective discussed in the above Strategic Research Agenda has an element of harmonisation. That is, 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 European Commission acknowledged the need for harmonisation in dosimetric practices in Europe, and publication of the Council Directive 96/29 EURATOM (13 May 1996) had major implications for individual monitoring. This document requested individual monitoring to be performed by approved dosimetry services, generalized the use of the operational dosimetric quantities, and placed an increased importance on quality assurance (QA) and quality control (QC) measures and their application to the routine work of individual monitoring services (IMSs). In reaction to the initiative of the European Commission, in December 1996 EURADOS set up an action entitled "*Harmonization of dosimetric quality assurance in individual monitoring of external radiation*" with the main aims of assisting the consolidation within the EU of the quality of individual monitoring using personal dosimeters and to facilitate harmonized procedures. Meanwhile requirements on individual monitoring services (IMS) were defined and quality management standards were set that highlight the technical competence of staff, and requests technical procedures to be used, in order to guarantee that any IMS is capable of generating technically valid results. These standards also require IMSs to regularly take part in inter-laboratory comparisons.

In some countries, national performance tests are offered, and successful participation is necessary for an IMS to be officially approved and allowed to maintain the activity as a service provider. In other countries, however, such organized exercises do not exist and it seems likely that the International Atomic Energy Agency (IAEA) will favour regions of the world other than the European region. EURADOS experience in this field may prove useful in the future.

As far as environmental monitoring is concerned, in Europe, at present, more than 4,500 stations provide almost real-time radiological monitoring data. In case of a radiological emergency with trans-boundary implications in Europe, national dose rate data must be reported to the European Commission (EC) on an hourly basis, via the European Radiological Data Exchange Platform (EURDEP). Based on these and other radiologically relevant data, the EC – being in charge of the European Community Urgent Radiological Information Exchange System (ECURIE) – may issue recommendations to the EU member states which could affect millions of people and may have severe economic and sociological consequences. Thus, reliable monitoring data of ambient dose rates, coordinated with data from other international radiological networks, are indispensable for adequate environmental radiation monitoring in Europe. The harmonisation of ambient dose rate measurements in Europe is a prerequisite for the reliability of the ECURIE system and an important contribution to its quality assurance.

In view of the need to harmonize dosimetric practices (both for individuals and the environment), and based on the interest of the European Commission and the earlier EURADOS activities

described above, EURADOS will continue with such activities in the future. These are described in the following sections.

## 5.1 Intercomparison for dosimeters used in individual monitoring

For individual monitoring it is our vision to create a long-lasting self-sustained system of actions that ensures harmonised dosimetric practises in Europe and that will contribute through participants from overseas (US, Japan) to a world-wide system of harmonised individual monitoring services.

First, this requires a network of contacts that in the ideal case should include one person per interested country, who would participate in and contribute to the relevant EURADOS activities. Depending on the type of information necessary, this individual would contact the IMSs and/or national radiation protection authorities in his/her own country and/or neighbouring countries. At present such a network has already been established including contacts with persons of all EU member states as well as Switzerland, Norway, Ukraine and Turkey. Keeping our vision in mind to extend this concept to regions outside Europe, this network needs to be expanded in the future and strategic contacts need to be established with regions outside Europe.

Second, this requires organisation of intercomparison exercises at accredited (EN ISO/IEC 17025) metrology laboratories for the required irradiations, collection and analysis of results declared by participants, preparation of certificates to participants, and eventually organization of a participants' meeting to report and discuss the overall results. In general, such a meeting is held at EURADOS Annual Meetings. Dissemination of the results will be done through EURADOS reports, presentations at conferences attended by the community and publications in peer-reviewed scientific journals.

So far, three whole-body photon intercomparison exercises were organized with a two-year interval (see Appendix). This meets the IMS needs to comply with EN/ISO/IEC 17025 requirements for accreditation. This concept proved very successful and it is our vision that it will be continued in the future on a regular basis. More specifically, our future plans include organisation of intercomparisons for whole-body dosimeters for photon fields, every 2 to 3 years, and with a smaller frequency for extremity dosimeters and neutron dosimeters (3 to 5 years interval).

The experience gained by EURADOS in the realization of such actions in the past may prove useful to other organizations such as IAEA and collaboration may be useful in organising similar actions in other parts of the world.

## 5.2 Intercomparison for early-warning systems used in environmental monitoring

For environmental monitoring it is our vision that contamination levels down to a few kBq/m$^2$, which correspond to an increase of the ambient dose equivalent rate ($H^*(10)$) of about 5 nSv/h (about 5 % of the natural background) from, for example, $^{137}$Cs, can be determined in the fastest possible way. We note that in case of a major radiological emergency, an early and reliable assessment of contamination levels of farmland and of dose rate levels in urban areas are of key importance for the protection of the health of the public against dangers arising both from direct 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, e.g. EURDEP, will be required. For this purpose, existing reference field stations, such as Intercal of BfS in Freiburg, Germany, and those presently under construction, e.g. the future underground calibration facility of IFIN-HH at Slanic-Prahova in Romania, should be metrologically linked with the primary standard facilities available for dosimetry at low dose rates. Currently, there is only one traceable calibration service for low dose rates (100 nSv/h and below) available worldwide, i.e., the underground facility UDO II, operated by PTB in Braunschweig, Germany. The Romanian installation may help to improve the calibration capabilities, especially for East-European countries which have not yet participated in intercomparison exercises such as those organised by EURADOS.

EURADOS intends to support operators of national early warning dosimetry networks and consult regulatory bodies and the Joint Research Centre (JRC) Ispra concerning legal aspects of environmental radiation monitoring, especially those related to Article 35 and 36 of the Euratom Treaty. The stimulation of cooperation, especially between the Institute for Environment and Sustainability (IES) with regard to EURDEP (European Radiological Data Exchange Platform) 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.

## 5.3 Surveys on practical dosimetry

Accreditation is gradually becoming more and more important for European IMS, and quality assurance and quality control is a central element. Here EURADOS can play a leading part in the future, if the actions mentioned above (intercomparison exercises, training courses) can be organised in a self-sustained manner. Monitoring the success of these actions is of course important, and regular surveys should be instigated by EURADOS, to document the quality of dosimetric practises in Europe and to compare it to that in other regions of the world. A survey organised by EURADOS in 2012-2013, for example, indicated that the profile of QA is high amongst the responding IMS and that most are following good practice. The majority of services are certified (around 70%) or declared themselves compliant to quality standards, mostly in accordance with EN/ISO/IEC 17025 (or with ISO 9001). These results, while in general very promising, suggest that further and continuous efforts must be made to guarantee a sustained, long-lasting, and consistent quantification of exposures to ionizing radiation.

In general, dissemination of the results should be done through EURADOS reports, presentations at conferences attended by the community and publications in peer-reviewed scientific journals. To support dissemination, the EURADOS network is involved in the organization of the conferences on individual monitoring as members of the scientific committees, invited lecturers, session chairs, co-chair and rapporteurs, referees for the preparation of proceedings, etc. So far Individual Monitoring conferences were organized in 2000 (Helsinki, Finland), 2005 (Vienna, Austria), and 2010 (Athens, Greece), and another is planned to take place in 2015 in Bruges (Belgium).

To ensure optimum use of the lessons learned from surveys and intercomparison exercises, 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 maintaining, updating and extending the contact details of interested IMS, regularly assessing the performance

of the participating IMS, in compliance with reference documents that are based on the analysis of EURADOS surveys and intercomparison results, and preparing training courses adapted to the identified lessons learned.

In order to keep dosimetric practises up-to-date, current and future ICRP and ICRU concepts and recommendations as well as corresponding EU Directives must be continuously scrutinized and their potential implications on measurement quantities, phantoms, etc. evaluated. Additionally, any new technical developments with respect to passive dosimeters (traditional film, TLD, OSL, track-etch, etc.) and in particular to active personal dosimeters must be also included in this evaluation.

Following the publication of ICRP60 in 1991 and ICRP103 in 2007 and although the radiation and tissue weighting factors were revised, the system of quantities suggested by ICRP and ICRU seems to be stable, namely, $H_p(d)$ for the next period. However, recent work on radiation effects suggested that the $H_p(3)$ quantity might deserve further attention, particularly with the decrease of the corresponding annual dose limit for the lens of the eye. As a consequence, the measurement of this quantity received increased importance as the output of recent projects show: (i) dedicated dosimeters have been proposed for the measurement of $H_p(3)$ closer to the eye lens; (ii) a cylindrical phantom as surrogate of the head instead of the slab phantom to be used for calibration of eye-lens dosimeters has been proposed; (iii) conversion coefficients for $H_p(3)/K_a$, $H_p(3)/\Phi$ for photons, electrons and neutrons (for both cylindrical and slab phantom) have been published by various authors in the open literature to complement the values published by ICRU/ICRP as international agreed values for $H_p(10)$, $H_p(3)$ and $H_p(0,07)$; (iv) international standards on procedures for the calibration of dosimeters in terms of $H_p(3)$ have not been updated yet. In the near future, the use of $H_p(3)$ in routine and related measurement procedures may be expected. Important QA and QC issues for $H_p(d)$ might also include the quantity $H_p(3)$ and related measurement issues and/or problems.

## 5.4 Intercomparison of dose assessment in cases of internal exposures

Doses from intakes of radionuclides cannot be measured directly but are estimated from monitoring data of activity in total/partial body and in excreta samples (urine and faeces). Such assessments require application of biokinetic and dosimetric models, and assumptions about the pattern of intake and the properties of the radioactive material inside the body. Past intercomparison exercises (Doerfel 2000, Hurtgen 2005) 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.

Intercomparison exercises of dose assessment in cases of internal exposures are required to validate the capability of the dosimetrists in the correct interpretation of monitoring data to provide the best estimate of the intake and Committed Effective Dose E(50).

The last international intercomparison exercise on internal dose assessment was organized by the IDEAS Group (IDEAS Project,EU Contract No. FIKR-CT2001-00160) in 2005. A new action is required taking into account the state-of-the-art tools currently available and forthcoming publications as follows:

- ICRP/OIR Reports: Occupational Intakes of Radionuclides (in progress). A series of documents that will replace the ICRP Publications 30, 54, 68 and 78, to provide revised dose coefficients and bioassay data for occupational intakes of radionuclides by inhalation and ingestion. The revised dose coefficients have been calculated using the ICRP100 Human Alimentary Tract Model (HATM) and a revision of the Publication 66 Human Respiratory Tract Model (HRTM). In addition, information will be provided on absorption in blood following inhalation and ingestion of different chemical forms of elements and their radioisotopes. Revisions have been made of many systemic models with more physiologically realistic representations of uptake and retention in organs and tissues and of excretion. The reports will also include some guidance on monitoring programmes and interpretation of bioassay monitoring data.
- Revised IDEAS Guidelines for the Estimation of Committed Doses from Incorporation Monitoring Data (EURADOS Report 01-2013, Casstellani et al). The IDEAS Guidelines are based on a general philosophy of a) harmonisation – by following the Guidelines any two assessors should obtain the same estimate of dose from a given data set, b) accuracy – the "best" estimate of dose should be obtained from the available data, and c) proportionality – the effort applied to the evaluation should be proportionate to the dose – the lower the dose, the simpler the process should be.
- ISO Standards in internal dosimetry, generated by ISO TC85/SC2/WG13

EURADOS has been involved in the organization of intercomparison exercises on dose assessments at an international level for many years and will take the initiative in organizing the next exercise after the publication of the new ICRP/OIR Reports. A plan of intercomparisons and training actions will be established for the next decades to help the internal dosimetry community to deal with intakes of radionuclides.

## 5.5 Intercomparisons of computational methods in dosimetry

Computational methods form a part of the work programme of all EURADOS Working Groups and a high fraction of papers published in radiation protection and dosimetry. These methods have moved from the domain of experts to become routine tools, which are commonly given to the most junior scientists in research teams, partly because of their IT skills. Those scientists may have the poorest understanding of the physics issues which are, however, crucial to the correct application of the code. Many of the codes that are now available can be obtained and installed with relative ease, and the manual may be used instead of any formal training, or the training may be provided informally in-house by those who are not expert and but who may already employ some practice.

Intercomparisons have been performed 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. Consequently, where misapplied, these methods can cause the cost and time savings available to be lost. Worse, they can lead to underestimates of risk or overprotection where, for example, vastly more expensive shielding is installed than is necessary.

Recent and ongoing intercomparisons have included:

- Design and calibration of a linac: a complex modelling problem involving the full design process and the characterization of the radiotherapy radiation field.
- Neutron energy distribution unfolding: computer models have been developed in which the neutron field is simulated. Bonner sphere detectors have been placed within these models to simulate the response and provide data for the unfolding process.
- Implementation of the ICRP reference phantoms: these are supplied in voxel form for the used to convert to the appropriate input for their computer code. This intercomparison will test both the ability of the user to construct the voxel phantom from the data provided, but also their ability to use the model to calculate the appropriate dose quantities.
- Micro and nano scale track structure: these studies are fundamental to the radiation damage to human tissue that leads to detriment. These calculations are at the cutting edge of Monte Carlo methods, since they are pushing at the boundaries of the data that are available and even the uncertainty principle.
- To summarize, computational methods are important for help with planning and design, interpretation of results/experiments and for more fundamental studies, there is scope for poor application. Questionnaires performed by EURADOS in the past showed the poor level of quality assurance performed by those using these methods, a situation that is likely to have got worse as their use has become more and more widespread.

Although computational methods are important for help with planning and design, interpretation of results/experiments and for more fundamental studies, there is scope for poor application. Questionnaires performed by EURADOS in the past showed the poor level of quality assurance performed by those using these methods. This situation is likely to become even more critical in the future because it is likely that these codes will become more and more widespread. EURADOS continues to perform modelling intercomparisons, commonly as collaborations between Working Groups. These efforts need to be intensified.

# Appendix

## A.1. History of EURADOS

During a meeting of scientists involved in contracts with the European Commission held in September 1981 at Homburg/Saar, Germany, EURADOS was conceived. It was decided that the activities of EURADOS would be focussed on the collection, processing and dissemination of information on research in dosimetry of all types of ionising radiation, and on the practical co-ordination of ongoing research projects and joint planning of future programmes.

The required financial support was received within the various Framework Programmes of the EC. Over the years this changed from general support for the network to dedicated support for projects. In this period EURADOS was fully dependent on EC funding.

EURADOS has mainly been operated by setting up Working Groups on particular topics. Such groups were installed for performing specific tasks and are usually dissolved after these tasks have been fulfilled. Examples were Working Groups on skin dosimetry, assessment of internal dose, criticality accident dosimetry, development of individual dosimeters for external penetrating radiation, basic physical data for gas ionising devices, and radiation exposure of air crews. Often a Working Group organised a workshop or seminar at the end of its work programme, presenting and discussing its results and/or published a detailed report.

EURADOS was registered in 2001 as a "society with restricted authority" at the chamber of commerce in the Netherlands. In particular the fact that the personal liability of the Council members was not restricted no longer allowed EURADOS to be a direct contractor in EC-funded projects. In addition, EURADOS was unable to organize self-supporting actions, such as intercomparison exercises, which may include a financial risk.

In 2007 the General Assembly initiated the change of EURADOS into a self-sustained network and a new legal entity. This was accomplished in 2008.

In the past, the European Commission has continuously shown interest in dosimetry issues. For example, end of 2006 the Commission issued a call for tender for the preparation of new European technical recommendations for monitoring individuals occupationally exposed to external radiation that would replace EUR 14852. In the resulting EU-Trimer project, EURADOS was instrumental in establishing a consortium and writing a document that was the result of a wide consensus of national radiation protection bodies, national metrology laboratories, authorities, standardization bodies (ISO, IEC), European IMS, etc. The final document was approved by the Group of Experts established under Article 31$^{st}$ of the EURATOM Treaty, and published by EC DGE as Radiation Protection n. 160 in November 2009.

## A.2. Current Status of EURADOS

The European Radiation Dosimetry Group (EURADOS) comprises a network of more than 60 European institutions (Voting Members) and 300 scientists (Associate Members). The aim of the network is to promote research and development and European cooperation in the field of dosimetry of ionizing radiation. It includes experts, reference and research laboratories, and dosimetry services. This enables appropriate specialist groups to be formed in a timely manner to

solve scientific problems or promote research identified within EURADOS or upon request from external bodies.

EURADOS e. V. was registered 2008 in the German Register of Societies as non-profit association, exempted from income tax. The rules of the association are governed by a constitution, complemented by "Rules of Procedure" to define further details. EURADOS Voting Members are institutions performing or promoting research in dosimetry. Each Voting Member nominates a permanent representative (delegate) who attends the General Assembly. The General Assembly is responsible for the governance of EURADOS and for the approval of objectives and strategy. The General Assembly elects the Chairperson and Vice-Chairperson of EURADOS. EURADOS is administered by this Council consisting of at least eight but no more than twelve associate members. The elected Chairperson and Vice-Chairperson are automatically members of the Council. Four Council members, so-called officers (Chairperson, Vice-Chairperson, treasurer, secretary) comprise the Executive Board which runs the daily work of EURADOS. The Council itself can install or close Working Groups, which in turn are comprised of individuals – so-called Associate Members – whose application must be approved by the Council. EURADOS may be supported by "Supporting Institutions" such as dosimetry services, manufacturers, and other institutions such as ICRU, ISO, IAEA etc. The main bodies of the association and their relationship are shown in Fig. A.1.

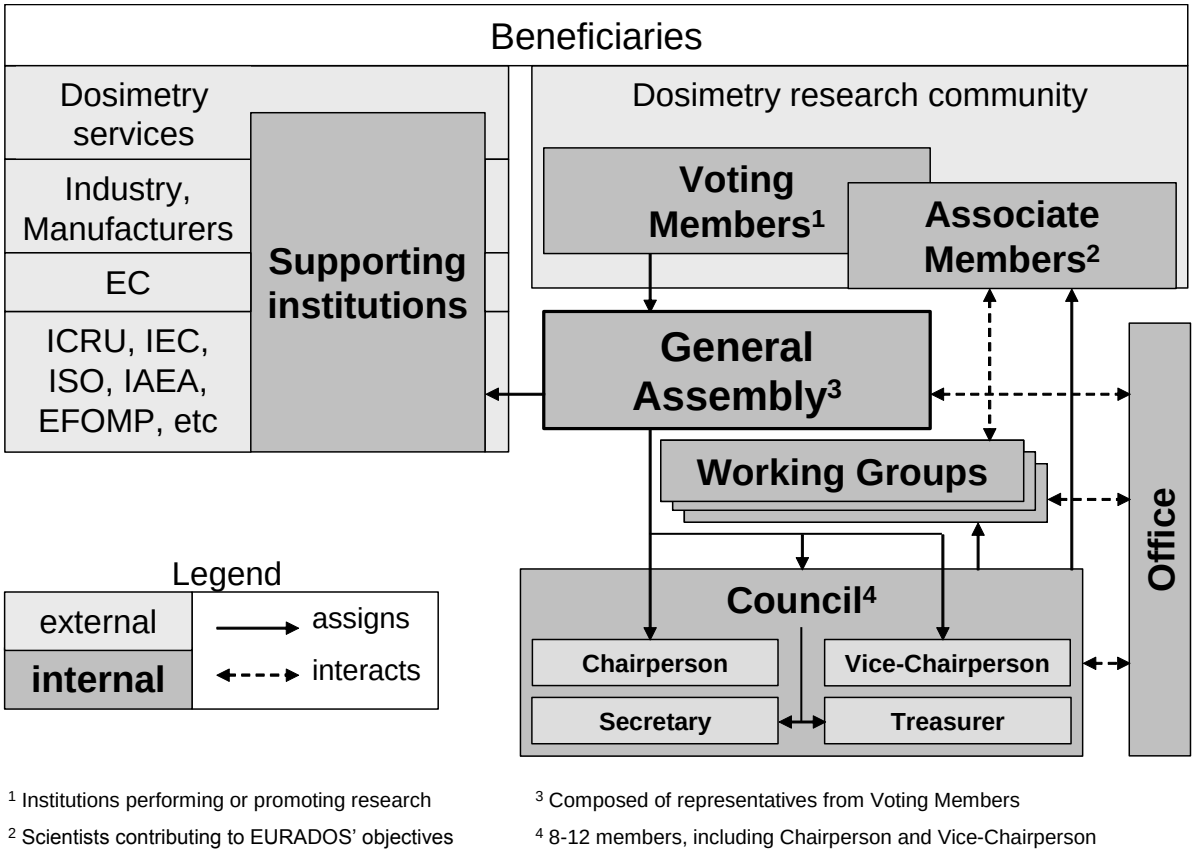


Fig. A.1: EURADOS as an organisation

The network's financial resources originate from sponsoring institutions, from voting members, from levies raised for activities organized by EURADOS (annual meetings, training courses and intercomparison exercises), and from projects funded by the European Commission. Due to this structure, EURADOS is a self-sustainable network.

**Areas of activities – science**

EURADOS activities encompass a) coordination of Working Groups that promote technical developments in radiation dosimetry and their implementation in routine work which contribute to compatibility and harmonisation within Europe and conformance with international practices, b) organization of scientific meetings and training activities and c) organization of dosimetry intercomparisons and bench mark studies.

The core of EURADOS activities is aimed at promoting scientific and technical research and development in the field of ionizing radiation. The work is performed in Working Groups (WG) which are composed of Associate Members. Scientific actions include individual monitoring for external exposure, individual monitoring for internal exposure, retrospective dosimetry, environmental radiation monitoring, diagnostic and interventional radiology, nuclear medicine, radiation therapy, and computational dosimetry. These scientific areas are reflected in the various Working Groups established by EURADOS. Currently (May 2014) EURADOS includes eight Working Groups that deal with certain aspects of research and harmonization in dosimetry:

- WG2: Harmonization of individual monitoring in Europe: Chair - João Alves, IST, PT
- WG3: Environmental dosimetry - Chair: Stefan Neumaier, PTB, DE
- WG6: Computational dosimetry - Chair: Rick Tanner, PHE, UK
- WG7: Internal Dosimetry - Chair: Maria Antonia Lopez, CIEMAT, ES
- WG9: Radiation protection dosimetry in medicine - Chair: Roger Harrison, Newcastle, UK
- WG10: Retrospective dosimetry - Chair: Clemens Woda, HMGU, Germany
- WG11: High energy radiation fields - Chair: Werner Rühm, HMGU, Germany
- WG12: European Medical ALARA Network - Chair: Zeljka Knezevic, Croatia

Members of Working Groups, Voting Members, and Council members meet regularly once a year during the Annual Meeting typically held end of January or early February. Annual Meetings are an opportunity for Working Group members to meet for 1 to 2 days and at the same time participate in Winter Schools and Workshops, and the representatives of voting members may take part in the General Assembly. A reasonable attendance fee is generally necessary to cover the organizing expenses and generate a small, positive balance.

Additionally, the Working Groups meet in summer or autumn for plenary Working Group meetings, complemented if necessary by meetings of task groups as defined within the Working Groups.

**Areas of activities – training and education**

EURADOS training actions include winter schools, workshops and training courses. In order to respond to the need for training in the field of radiation dosimetry, EURADOS Winter Schools were included in the Annual Meetings for the first time in 2007. Topics are selected based on suggestions from Voting Members or the Council. In addition various training courses have been organised. A list of past Winter Schools, Workshops, and training courses is given below.

The following Winter Schools were held during Annual Meetings:

- Relative Biological Effectiveness, Radiation Weighting Factor and Quality Factor: Their Role in Quantifying Effectiveness of Ionizing Radiation (AM2014)
- Status and Future Perspectives of Computational Micro- and Nanodosimetry (AM2013):
- Radiation Protection for Medical Staff (AM2011)
- Radiological Emergencies – Internal exposures (AM2010)
- Low-Dose Radiation Effects (AM2009)
- Retrospective Dosimetry (AM2008)
- Uncertainties in Radiation Dosimetry (AM2007)

The following Workshops were held during Annual Meetings:

- Dosimetry for second cancer risk estimation in radiotherapy (AM2012)
- Accelerator radiation protection and shielding (AM2010)
- Cosmic Radiation and Aircrew Exposure (AM2009)
- Dosimetric Issues in the Medical Use of Ionizing Radiation (AM2008)
- Characterization of Workplaces for the Assessment of the Doses to Individuals (AM2007)
- Uncertainties in Dosimetry – Principles Through to Practice (AM2006)
- Radiation Protection Dosimetry and Dosimetry for Medical Applications (AM2005)
- Biological and Physical Dosimetry for Radiation Protection (AM2004)

The following education and training actions were held as self-supporting actions:

- 2nd EURADOS Voxel Phantom School (HMGU, Neuherberg, 2014)
- 2nd EURADOS Training Course: European Technical Recommendations for Monitoring Individuals Occupationally Exposed to External Radiation (RBI, Zagreb, 2013).
- EURADOS WG7 - KIT Training Course on Monte Carlo Methods for calibration of body counters (KIT, Karlsruhe 2013)
- EURADOS Training Course: European Technical Recommendations for Monitoring Individuals Occupationally Exposed to External Radiation (CTU, Prague, 2012)
- EURADOS School on Retrospective Dosimetry – Practical exercise in Solid State & Cytogenetic dose reconstruction (HMGU, Neuherberg, 2012)
- EURADOS Voxel Phantom School (IRSN, Forntenay-aux-Roses, 2011)
- EURADOS/IAEA Regional Training Course on Advanced Methods for Internal Dose Assessment (CTU, Prague, 2009)

**Areas of activities – intercomparisons**

Intercomparisons and benchmark exercises are important tools for quality assurance. EURADOS carried out such activities on the areas of Individual Monitoring of External Radiation, Early Warning Radiation Monitoring Systems, Computational Codes in Radiation Dosimetry, Neutron Spectrometry, and Internal Dosimetry

The more recent actions (in brackets the Working Groups which carried them out) were:

- EURADOS Intercomparison 2014 for whole body photon dosimeters (IC2014) (WG2)
- EURADOS Intercomparison 2014 for passive environmental dosimeters (WG3)
- EURADOS Intercomparison 2012 for whole body neutron dosimeters (IC2012n) (WG2)

- EURADOS Intercomparison 2012 for whole body photon dosimeters (IC2012ph) (WG2)
- 6th EURADOS Intercomparison 2012 of Early Warning Dosimetry Network Systems (WG3)
- Measurements at high-energy neutron fields 2011 (WG11)
- EURADOS Intercomparison 2010 for whole body dosimeters (IC2010) (WG2)
- Intercomparison 2010 on Monte Carlo modelling of *in vivo* measurements of lung contamination with a Livermore phantom (WG6 and WG7)
- 5th EURADOS Intercomparison 2009 of Early Warning Network Systems (WG3)
- EURADOS Intercomparison 2009 for extremity dosimeters (IC2009) (WG2)
- EURADOS Intercomparison 2008 for whole body dosimeters (IC2008) (WG2).
- 3rd EURADOS Intercomparison 2006 to harmonise European early warning dosimetry systems (WG03):

Participation in such intercomparison exercises has always been successful and is even increasing; it now also includes IMSs from outside Europe, as data reported in the following table show:

| IC exercise | Number of participants | Number of dosimetry systems | European countries | non European countries |
|---|---|---|---|---|
| IC2008 | 52 | 62 | 19 | 2(i) |
| IC2009 | 44 | 59 | 18 | |
| IC2010 | 70 | 85* | 27 | 3(ii) |
| IC2012ph | 76 | 88 | 25 | 5(iii) |
| IC2012n | 27 | 34 | 15 | 3(iv) |
| IC2014 | 97 | 112 | 27 | 8(v) |

(*) IC2010, the participation of 9 systems was sponsored by the IAEA
(i) Turkey and Ukraine
(ii) Argentina, Turkey and Ukraine
(iii) Argentina, Israel, Turkey, Ukraine and USA
(iv) Israel, Japan and USA
(v) Argentina, India, Israel, Japan, Lebanon, Turkey, Ukraine, USA

**Sources of income and self-sustainability**

In all undertaken actions (intercomparison exercises, training courses, training schools, annual meetings) the revenue from the participants' fees is used to cover all expenses and preferably generate a positive balance.

In general, actions are carried out by an organizing group suggested by the Working Group and appointed by the Council following the analysis of a calendar and the approval of a preliminary budget. The budget includes manpower costs for the co-ordinator and collaborators respective institutes, consumables, travel and subsistence and other costs depending on the action, e.g. irradiation costs in the case of intercomparison exercises. Although travel and subsistence are covered at real costs, EURADOS counts on the collaboration of the home institutes particularly for manpower charges, that is, manpower is not charged at the real cost of dedicated amount of time

and/or work. On the other hand, the institutes also recognise the importance of the activity and increased visibility for their institution within the dosimetric community by taking part in the action.

At present 32 institutions and companies annually support EURADOS with a sponsorship fee.

**Other Conferences with support from the Eurados network**

EURADOS actively initiates and supports the continuation of a series of conferences on Individual Monitoring (IM) and Neutron- and Ion Dosimetry (NEUDOS). Past examples were IM2005 (Vienna), IM2010 (Athens), NEUDOS9 (Delft, Netherlands, 2003), NEUDOS10 (Uppsala, Sweden, 2006), NEUDOS11 (Cape Town, South Africa, 2009) and NEUDOS12 (Aix-en-Provence, France, 2013). In these cases, the EURADOS council took the initiative by calling for proposals to host the respective conference. The selection of the organizer and venue was then done by the EURADOS Council and the members of the scientific committee of the previous conference.

In addition, EURADOS provides financial support for other conferences where dosimetry is an important topic. Examples are EPR-BioDose 2010 (Mandelieu-La-Napoule), France, and 2013 (Leiden, The Netherlands) and the 5$^{th}$ MELODI workshop (Brussels, Belgium, 2013).