Quality assurance for the use of computational methods in dosimetry: activities of EURADOS Working Group 6 “Computational Dosimetry”

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H. Rabus[1], J. M. Gómez-Ros[2], C. Villagrasa[3], J. Eakins[4], T. Vrba[5], V. Blideanu[6], M. Zankl[7], R. Tanner[4], L. Struelens[8], H. Brkić[9], C. Domingo[10], G. Baiocco[11], B. Caccia[12], C. Huet[3], P. Ferrari[13]

[1] Physikalisch-Technische Bundesanstalt (PTB), Abbestrasse 2-12, 10587 Berlin, Germany
[2] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[3] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France
[4] Public Health England (PHE), Didcot, United Kingdom
[5] Czech Technical University in Prague (CTU), Prague, Czech Republic
[6] Commissariat à l'énergie atomique et aux énergies alternatives (CEA), Saclay, France
[7] Helmholtz Zentrum München German Research Center for Environmental Health (HMGU), Neuherberg, Germany
[8] Belgian Nuclear Research Center (SCK•CEN), Mol, Belgium
[9] J. J. Strossmayer University of Osijek (MEFOS), Osijek, Croatia
[10] Universitat Autonoma de Barcelona (UAB), Barcelona, Spain
[11] Physics Department, University of Pavia, Pavia, Italy
[12] National Institute of Health (ISS), Rome, Italy
[13] National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy

E-mail: **hans.rabus@ptb.de**

Abstract

Working Group (WG) 6 "Computational Dosimetry" of the European Radiation Dosimetry Group (EURADOS) promotes good practice in the application of computational methods for radiation dosimetry in radiation protection and the medical use of ionizing radiation. Its cross-sectional activities within the association cover a large range of current topics in radiation dosimetry, including more fundamental studies of radiation effects in complex systems. In addition, WG 6 also performs scientific research and development as well as knowledge transfer activities, such as training courses.

Monte Carlo techniques, including the use of anthropomorphic and other numerical phantoms based on voxelized geometrical models, have a strong part in the activities pursued in WG 6. However, other aspects and techniques, such as neutron spectra unfolding, play an important role as well. A number of intercomparison exercises have been carried out in the past to provide information on the accuracy with which computational methods are applied and whether best practice is being followed. Within the exercises that are still ongoing, the focus has changed towards assessing the uncertainty that can be achieved with these computational methods. Furthermore, the future strategy of WG 6 also includes an extension of the scope toward experimental benchmark activities and evaluation of cross-sections and algorithms, with the vision of establishing a gold standard for Monte Carlo methods used in medical and radiobiological applications.

Keywords: Computational methods, dosimetry, ionizing radiation, quality assurance

1. Introduction

The European Radiation Dosimetry Group (EURADOS) e.V. is an association of more than 70 European institutions and about 600 individual scientists as associate members. The mission of EURADOS is to promote the scientific understanding and technical development of dosimetry in the fields of radiation protection, radiobiology, and medical use of ionizing radiation (e.g. radiation therapy and diagnostic radiology) by stimulating collaboration between European research institutions. Currently, EURADOS has eight Working Groups (WGs), which organize scientific meetings, training activities, intercomparisons, and benchmark exercises for promoting quality assurance (Rühm *et al* 2015, 2018, Alves *et al* 2019, Rühm *et al* 2020).

WG 6 "Computational Dosimetry" has a cross-sectional role and promotes good practice in the application of computational methods for radiation dosimetry in radiation protection and the medical use of ionizing radiation. As computational methods are widely used in radiation protection and other areas of radiation dosimetry, e.g. in the design of experiments and in the interpretation of results, WG 6 strongly engages in collaborations with the other WGs that are focused on various subject areas of practical dosimetric application (e.g. Harmonization of Individual Monitoring, Environmental Dosimetry, Internal Dosimetry, Dosimetry in Radiotherapy, Retrospective Dosimetry, High-Energy Radiation Fields, and Dosimetry in Medical Imaging) rather than the underlying computational techniques themselves. These collaborations cover a large range of current topics in radiation dosimetry, including more fundamental studies of radiation effects in complex systems. In addition, WG 6 also performs scientific research and development as well as knowledge transfer activities, such as training courses.

Monte Carlo techniques, including the use of anthropomorphic and other numerical phantoms based on voxelized geometrical models, have a strong part in the activities pursued in WG 6. However, other aspects and techniques, such as neutron spectra unfolding, play an important role as well. As a hybrid activity between knowledge transfer and research, a number of intercomparison exercises have been carried out in the past where participants were invited to solve predefined computational problems with some freedom in choosing their methodology and approach (Tanner *et al* 2004, Gualdrini *et al* 2005, Siebert *et al* 2006, Price *et al* 2006, Gómez Ros *et al* 2007a, 2007b, 2008a, Gualdrini *et al* 2008, de Carlan *et al* 2008, Lopez *et al* 2010a, Broggio *et al* 2012, Barros *et al* 2014, Vrba *et al* 2014, 2015, Caccia *et al* 2017, Gómez-Ros *et al* 2018, Villagrasa *et al* 2019, Li *et al* 2020a); the participants' results could then be compared, in an effort to investigate common successes and difficulties, provide practical feedback, and learn lessons. Participation in the exercises is open to everybody, and participants have been solicited by announcements on the EURADOS website (www.eurados.org) and in the regularly issued EURADOS newsletter as well as through conference papers and publications (Tanner *et al* 2004, Gualdrini *et al* 2005).

The main purpose of such exercises was to provide information on the accuracy with which computational methods are applied and whether best practice is being followed. However, within some of the exercises that are still ongoing, i.e. neutron spectra unfolding (Gómez-Ros *et al* 2018) and investigations of the cross-sections used as input parameters in track structure codes (Villagrasa *et al* 2019), the focus has changed towards assessing the uncertainties that are associated with these computational methods. Furthermore, the future strategy of WG 6 also includes an extension of the scope toward experimental benchmark activities and evaluations of the cross-sections and algorithms underlying the computations, with the vision of establishing a gold standard for Monte Carlo methods used in medical and radiobiological applications.

EURADOS WG 6 presently has 29 full members and 24 corresponding members (individuals that contribute to the WG work without formal membership in the EURADOS association). Traditionally WG 6 has been sub-divided into task groups (TGs) that cover a range of activities, but there is considerable interaction and working across the different TGs, along with other WGs.

2. Tasks within WG 6

2.1. Neutron spectra unfolding

Task 1 on neutron spectra unfolding deals with the computational tools related to neutron spectrometry, as a prerequisite for the dosimetric assessment of the neutron component of radiation fields. Neutron dosimetry is a particular challenge in radiation protection, as there is a pronounced energy dependence of the biological effects of neutrons and the neutron energies may be spread over more than ten orders of magnitude (ICRP 2007). As neutrons are indirectly ionizing particles, they are generally detected via the recoil protons produced in nuclear reactions. To cover the large relevant energy range, sets of so-called Bonner spheres (BSs) are used, which feature a central sphere filled with ^{3}He that is surrounded by spherical shells of polyethylene of different thickness and different inner and outer coatings of suitable metals. By neutron interactions in the BS, their energy spectrum changes. The materials and sizes of the BSs are chosen such that through this moderation process different parts of the incident neutron energy spectrum are matched to the resonance of the production of tritium (^{3}H) by neutron capture of ^{3}He.

A neutron field measurement thus consists of a set of count rates from the different BSs, which then needs to be transformed into information on the neutron energy spectrum via spectrum unfolding techniques. A number of codes are used for this purpose, and one of the main activities of the task group has been analysis of the performance of those different tools (Barros *et al* 2014). Currently, the task is focused on conducting an intercomparison exercise on reconstructing neutron spectra from the knowledge of the system response function and the values of counts obtained with a set of Bonner spheres. In addition, the task group is engaging in a joint activity with EURADOS WG 11 "High Energy Radiation Fields" to prepare a training course on neutron spectra unfolding, which is planned to take place in 2021.

Within the BS spectra unfolding exercise organized by task group 1, participants were invited to unfold BS data using a unfolding tool of their choice (Gómez-Ros *et al* 2018), having been provided with limited information about the nature of the neutron field and the calculated response matrices for idealized BSs. The BS data consisted of the count rates and measurement uncertainties of a set of 13 BSs, which were calculated by the organizing team using Monte Carlo simulations of the experimental setups.

The following four scenarios for BS measurements of neutron fields were considered: 1. at two points near a medical linear accelerator in a treatment room with a maze; 2. in a simulated workplace field; 3. inside an irradiation room with a radionuclide source in an iron sphere; 4. environmental measurement at 100 m from a nuclear plant ("sky shine scenario").

For each case a reference solution was determined before the start of the exercise by members of the task group who were not involved in the simulation of the BS counts given to the participants, such as to ensure that the problems were solvable. At present, analysis of the solutions delivered by the 20 participants from 15 countries worldwide using 14 different unfolding techniques is close to completion and a paper on the results is in its drafting stage.

2.2. Micro- and nanodosimetry

Task 2 on micro- and nanodosimetry has its major activities in: investigating the uncertainty associated with track structure Monte Carlo simulations; and fundamental issues in track structure calculations, such as conceptional questions with scoring the energy deposition pattern in charged particle tracks and the relevance of quantum effects in track simulations. Furthermore, the task group also supports the efforts of the international Geant4-DNA collaboration to include cross-sections for materials other than liquid water in their database. Major activities at present concern a code intercomparison exercise for estimating uncertainties in micro- and nanodosimetric simulations (Villagrasa *et al* 2019) and a code intercomparison exercise held jointly with WG 7 "Internal dosimetry" on the dose enhancement around gold nanoparticles (Li *et al* 2020a, 2020b, Rabus *et al* 2020).

Within the two-step "uncertainty" exercise, the goal of the first step is to use the discrepancies between results of different codes to estimate an uncertainty budget for the cross-sections for low-energy electron scattering in liquid water, which are the most likely cause of the discrepancies. The exercise was defined by a given simulation setup (i.e. specified source and 'detector' geometry, electron source energy spectrum, etc.) for which the microdosimetric specific-energy spectrum or the nanodosimetric cluster size distributions were to be calculated (Villagrasa *et al* 2019). The microdosimetric mean quantities calculated by the participants in this exercise generally agreed well (within a few percent), suggesting that all codes employed in this part of the exercise can be applied with radiobiological models that relate microdosimetric quantities with biological effects. In the second step of the exercise it was planned to implement a unique cross-section data set in different track structure codes, together with the estimated uncertainties. The task was then to transport those uncertainties through the simulation, to get the uncertainty component of the simulation results that originates from the uncertainty of the cross-sections. Given that the nanodosimetric radiation quantities obtained in the first part of the exercise exhibited such large discrepancies that they would require the uncertainty to be assumed to be as high as 100%, this second part of the exercise is currently under redefinition.

In the joint code intercomparison exercise with WG 7, the participants were asked to simulate the emitted electron spectrum and the microscopic dose deposition around gold nanoparticles for x-ray irradiation in a simple, idealized geometry that consisted of a pencil beam of comparable diameter to the nanoparticle (Li *et al* 2020a). This artificial situation was meant to emphasize the differences in interaction cross-sections that could be expected, which is particularly important because the radiation interaction cross-sections of low-energy electrons in gold have not yet achieved the same level of evaluation as the cross-sections for interactions in water. In the first analysis, the ISO Guide to the expression of Uncertainty in Measurements (GUM) was employed (ISO 1995) to interpret the reported results as independent measurements and to derive an uncertainty estimate for the dose enhancement by gold nanoparticles, where the probability distribution function had to be assumed to be log-normal to account for the large spread of the results. Further analysis revealed that the large differences between the reported results could be traced back to conceptional misunderstanding and improper implementations of the exercise (Li *et al* 2020b, Rabus *et al* 2019).

2.3. Individual monitoring

Task 3 is concerned with Monte Carlo simulations for individual monitoring in radiation protection. As computational methods play an important role in designing and evaluating the dosemeters and instruments used to assess the operational quantities, the task group is engaging in collaboration with WG2 "Individual Monitoring" to provide a training course on the use of Monte Carlo techniques for this purpose. In addition, the task group has also been contributing to a cross-WG activity on producing a report that intends to aid and guide the radiation dosimetry community following the imminent change to the operational dose quantities proposed by the International Commission on Radiation Units and Measurements (ICRU) (ICRU 2020). One further recent major research activity conducted by this task group is related to retrospective dosimetry, performed in collaboration with WG10 "Retrospective Dosimetry". The aim of this work is to develop the means for relating the dose measured by a retrospective dosemeter (e.g. glass and electrical components of a mobile phone) to the detriment to the individual, where the relationship is a function of location, orientation, exposure geometry and energy. This encompasses: the exploration of optimum dose quantities for use in scenarios encountered in nuclear emergency and accident situations (Eakins and Ainsbury 2018a, 2018b); the generation of a database of conversion coefficients from absorbed dose-related signals measured from mobile phone components to organ doses, for the most relevant exposure sources (e.g. (at present) ^{137}Cs, ^{60}Co, ^{131}I and ^{192}Ir radionuclides, as well as 100 keV x-rays) and for different irradiation geometries; and the development of conversion algorithms that incorporate the database and can easily be used in emergency scenarios. In addition, a new research activity is under development by this task group that relates to skin dosimetry, and in particular the generation of an improved skin model. This work aims to address the problem that the voxel size in the presently used numerical ICRP phantoms for the standard male and female (ICRP 2009) are too big to capture details of the skin that become relevant for short-ranged charged particles: the skin model of ICRP publication 118 considers dermis and epidermis as unstructured layers of different thickness depending on the location on the body (ICRP 2012), which may not be sufficient in particular for stochastic effects or very inhomogeneous exposures, such as from "hot" (radioactive) particles.

2.4. In-vivo dosimetry

Task 4, on in-vivo dosimetry, has been terminated recently after a long record of joint activities in collaboration with WG 7 "Internal Dosimetry". Those activities encompassed a series of intercomparison exercises on dose assessment from in-vivo measurements of radionuclide contamination in the lung, in the knee, or in the skull (Gómez Ros *et al* 2007a, 2007b, Moraleda *et al* 2007, Gómez-Ros *et al* 2008a, Lopez *et al* 2010a, Broggio *et al* 2012, Vrba *et al* 2014, 2015, López *et al* 2019). In the most recent such exercise, on the determination of the activity of the nuclear fall-out product ^{241}Am in the human skull, intercomparisons of Monte Carlo simulations were performed for three levels of complexity of the simulation problem (Vrba *et al* 2014, 2015). In the lowest complexity level, the response function of a given detector measuring a defined numerical skull phantom was to be simulated for a completely defined measurement geometry and given material data (Vrba *et al* 2014). The intermediate complexity problem encompassed simulation of a real detector where the relevant material parameters and dimensions were to be retrieved by the participants for a detector of their choice. The highest complexity level related to a real measurement geometry, including the detectors and their placement with respect to the skull phantom (Vrba *et al* 2015). All three intercomparison parts were addressed by 15 or 16 participants, mostly using the MCNPX code (Pelowitz 2005), but there were also results produced using other codes, namely EGS4 (Nelson *et al* 1985), Geant4 (Agostinelli *et al* 2003) and VNC (Hunt *et al* 2003).

2.5. Linac modelling

Task 5 has been conducting an intercomparison exercise on the design and dosimetry assessment of a linear accelerator (LINAC) facility (Caccia *et al* 2017, 2020, Rühm *et al* 2020). In the first part of the exercise, participants were asked to determine the electron energy distribution and beam size impinging on the head of a LINAC operated at the French designated institute for ionizing radiation metrology (LNHB), using information provided on the LINAC head geometry and material composition as well as results from measurements of the lateral and depth-dose profiles in a water phantom that were performed at LNHB. In the second part of the exercise, simulations were to be performed starting from the photon source given by the LINAC head and the electron beam to obtain lateral and depth-dose profiles within simplified patient models, realized by a water phantom with inhomogeneities mimicking bone and lung tissue, i.e. denser or less dense material than water. Here, four cases were considered: (a) lung in water; (b) bone in water; (c) bone and lung in water; and (d) two lungs in water. The densities of the lung and bone "tissue" and the simulation geometry were provided as input for the simulations. Six participants provided solutions to the exercise, using four different Monte Carlo codes, namely Geant4 (Agostinelli *et al* 2003), EGSnrc (Kawrakow 2000), Tripoli 4 (Brun *et al* 2015) and MCNPX (Pelowitz 2005). Using a gamma index criterion as applied in clinical practice, the simulation results were again benchmarked with measurements performed at LNHB in real phantoms. The main conclusion from the exercise was that with respect to the first task to be solved, different electron beam parameters could equally well reproduce the measurements in a simple homogeneous water phantom, leading to significant discrepancies for the cases with heterogeneities (Caccia *et al* 2017, 2020). The simulation set-up used in the exercise has been adopted by the international Geant4 collaboration (Agostinelli *et al* 2003, Allison *et al* 2006) as an advanced example for self-training of new users of that code system.

2.6. Voxel phantoms

Task 6 is concerned with the implementation of voxel phantoms in Monte Carlo simulations, particularly for assessing radiation protection quantities (organ doses, effective dose). Significant contributions have also been made in the past to intercomparisons of in vivo dosimetry, in collaboration with Task 4 and WG 7 (Gómez Ros *et al* 2007a, 2007b, 2008b, Lopez *et al* 2010b). Another important activity has been conducting training courses on the implementation of voxel phantoms in Monte Carlo simulations (see Section 3). At present, the task group is focused on the final analysis stage of a group of intercomparison exercises that tested participants' capabilities to properly implement the ICRP reference computational phantoms (ICRP 2009) in Monte Carlo simulations and calculate organ doses (and from these, equivalent doses and the radiation protection quantity effective dose). The exposure scenarios considered were designed such that cases of occupational, accidental and medical exposures were covered, as well as several radiation types (photons, neutrons, electrons).

The occupational exposure scenarios were irradiation by a ^{60}Co photon point source or a monoenergetic 10 keV neutron point source, both with the source in front of the human body at 125 cm from the feet and 100 cm from the chest. The former scenario was addressed by 17 participants, while for the latter only 8 solutions were received.

The accidental exposure scenarios were: ground contamination with an ^{241}Am radionuclide distributed evenly within a disc of 2 m radius with the phantom standing in the center, which attracted 13 participants; and exposure in a room where the air is contaminated with the β emitting radionuclide ^{16}N, for which 6 participants delivered solutions. In the latter case, part of the exposure would be from inhaled ^{16}N radionuclides in the lung.

For medical scenarios, an idealized typical x-ray examination of the chest in PA geometry (irradiation from the back) and of the abdomen in AP geometry (irradiation from the front) was chosen. Here, the eight participants submitting solutions had to determine the location of the point source relative to the phantom co-ordinate system for the given target organ to be screened, and determine the organ absorbed dose conversion coefficients with respect to the dosimetric quantities air kerma (free in air) at the entrance skin surface of the body and kerma-area product (KAP). The latter two quantities would be measured in x-ray screening practices in the frame of quality assurance of the x-ray source.

A sixth exposure scenario was also proposed that considered the internal exposures occurring in occupational, accidental and medical situations. Here the task was to evaluate quantities relevant to dose assessment for artificial cases in which monoenergetic photons or electrons were emitted within specified source organs, and for cases in which the radiation was emitted by specific radionuclides. Twelve participants submitted solutions for this challenge.

For each of the six parts of the intercomparison, two members of the organizing group independently performed calculations before the exercise was announced, to ensure that the problems were solvable and that master solutions could be established. The participants were advised to use the reference computational phantoms as described in ICRP Publication 110, and recommended either to apply the method proposed in ICRP Publication 116 (ICRP 2010) for determining the doses to red bone marrow and bone surface or else describe in detail any deviating bone dosimetry method if they chose to use an alternative.

2.7. High energies

Task 7 on high energies collaborates closely with WG11 "High energy radiation fields" and WG9 "Radiation dosimetry in radiotherapy". In the past, the modelling of radiation protection devices was an important activity (Rollet *et al* 2009, Wiegel *et al* 2009, Silari *et al* 2009). More recently, Bonner sphere responses for high energy neutrons have been modelled and benchmarked with measurements (Rühm *et al* 2014). The discrepancies due to the different models employed in the various high-energy codes to generate neutron-scattering cross-section data for the energy domain from MeV to GeV remain an ongoing challenge. Currently, a literature review is being conducted to compile a summary of the capabilities of the codes in use. The definitions of intercomparison exercises that will aim to assess the implementation of these models in the codes are also in preparation.

2.8. WG 6 Strategy (formerly uncertainty and sensitivity assessment)

Originally established for addressing the overarching topic of uncertainties in computational dosimetry following the comprehensive Quality Assurance of Computational Tools for Dosimetry (QUADOS) exercise that had been conducted (Tanner *et al* 2004, Gualdrini *et al* 2005, Siebert *et al* 2006, Price *et al* 2006), task 8 is presently concerned with the steering and strategy of the working group. A major activity has been providing input to the Strategic Research Agenda of EURADOS (Rühm *et al* 2015, 2018).

2.9. Nuclear medicine

Task 9 engages with WG 12 "Dosimetry in medical imaging" and WG 7 "Internal Dosimetry", in a collaboration also with the European Association of Nuclear Medicine (EANM), on dosimetric issues related to diagnostic and therapeutic nuclear medicine. These topics include the doses received by carers / comforters of patients receiving nuclear medicine treatment, or doses to members of the public from persons who have undergone a nuclear diagnostic procedure. Currently the research is focused on the development of a computational approach for determining the external dose rates received by third-party individuals from nuclear medicine patients, for a set of specific geometries. Major challenges encountered in this context are related to the biokinetics of the radionuclides in the human body.

2.10. Radiotherapy and radiation diagnostics

Task 10 "radiotherapy and radiation diagnostics" was established in 2020 in response to an increased demand from WG9 "Radiation dosimetry in radiotherapy" and WG12 "Dosimetry in medical imaging" for support of their research projects by Monte Carlo simulations. Examples include: the assessment of surrounding healthy tissue doses in brachytherapy, where sources of encapsulated radionuclides emitting short-range photon or electron radiation are employed; and dosimetry issues with proton therapy, where unwanted irradiation of tissue outside the region targeted for treatment is a major concern, and may arise due to neutrons produced by nuclear collisions in the irradiated tissue, as well as in components of the irradiation facility used for shaping or moderating the proton beam. In both cases, data analyses of experimental measurements often require auxiliary information from radiation transport simulations. A further issue of high practical concern is the dose received by the fetus if the mother undergoes radiotherapy, e.g. before the pregnancy has been realized. Another major activity is a collaboration with WG 7 "Internal Dosimetry" and WG12 "Dosimetry in Medical Imaging" on dosimetry issues of emerging radiopharmaceuticals (e.g. ^{68}Ga, ^{177}Lu).

3. Education and training activities

A common insight from the intercomparison exercises in computational dosimetry referred to in the previous section is that a major source of uncertainty of the simulation results can be attributed to the code users (Siebert *et al* 2006, Price *et al* 2006). In contrast to analogous comparisons in metrology, for example, where the technical protocol is agreed in advance by participants who typically already have a track record of experience in the measurements to be performed, the intercomparisons in computational dosimetry have a different character. For instance, while the exercises are prepared by experts in the field and methodology, many of the participants are less experienced code users, often early stage researchers. Moreover, such users may be easily misled by the apparent ease of use that many general purpose Monte Carlo codes offer nowadays, or be tempted to believe that, for example, small standard deviations on their modelled results are a sign of low uncertainties overall (rather than being just a metric of statistical precision), or that dividing results by the number of primary particles simulated would be an appropriate normalization. Apart from annoying aspects that complicate data analysis, such as results not being reported using the provided templates and/or with binning structures different from those requested, the intercomparisons also often reveal naivety and conceptual misunderstandings of the simulation problem itself, as well as a lack of awareness that simulation results need to be checked for self-consistency and plausibility, such as being the obvious right order of magnitude or correct sign.

In most of the intercomparison exercises mentioned in the previous section, the task had been solved by two members of the respective task group to ensure that the problem was solvable and to obtain a master solution as the reference. In the evaluation of these intercomparison exercises, there has therefore usually been a feedback loop where participants were informed that their solution deviated more than expected from the master solution, and they were requested to provide further information on their simulations and to check their results. In quite a few cases, the participants then delivered revised results for which, in general, the deviation from the master solution would decrease, while still sometimes being significant (Vrba *et al* 2014, 2015, Li *et al* 2020b).

Table 1 Training courses and workshops delivered by EURADOS WG 6 in the past decade.

Activity	Place and dates
Organization of Training School on the development of voxel human geometries for Monte Carlo codes	Fonteny aux roses, France, 11-13 October 2011
Organization of 6th Winter School "Status and Future Perspectives of Computational Micro- and Nanodosimetry"	Barcelona, Spain, 6 February 2013
Co-organization of International Workshop on "Challenges in Micro- and Nanodosimetry for Ion Beam Cancer Therapy (MiND-IBCT)"	Wiener Neustadt, Austria, 7-9 May 2014
Organization of Training School on the development of voxel human geometries for Monte Carlo codes	Neuherberg, Germany, 13-15 May 2014
Contribution to 10th EURADOS Winter School "Internal dosimetry for radiation protection and medicine"	Karlsruhe, Germany, 2 March 2017
Contributions to 11th EURADOS Winter School "Application of physical and computational phantoms in dose assessment"	Lisbon, Portugal, 8 February 2018
Organization of EURADOS Training Course on the Application of Monte Carlo Methods for Dosimetry of Ionizing Radiation	Karlsruhe, Germany, 12-16 March 2018
Organization of Satellite workshop on micro- and nanodosimetry to the 3rd International Conference on Dosimetry and Applications	Lisbon, Portugal, 26 May 2019
Contributions to the 7th International Workshop on Computational Phantoms	Neuherberg, Germany, 22-24 July 2019

In some areas of computational dosimetry, and particularly in micro- and nanodosimetry, the rapid development of codes is an additional complication, as different codes may use different cross-section data or models for their implementation that can lead to significantly different results (Lazarakis *et al* 2012, Villagrasa *et al* 2019). In general, however, the outcomes of these exercises are snapshots of the state of the art in the field, not necessarily reflecting the capabilities of the codes, but rather the performance of code users. The group of participants may not even be a representative sample, as interest and willingness to take part in such voluntary exercises already perhaps demonstrates a level of awareness that may not be common within the community of code users.

Therefore, like the other working groups within EURADOS, WG 6 also contributes to EURADOS' mission of promoting harmonization and good practice in radiation dosimetry, by organizing and contributing to education and training events (Alves *et al* 2019), such as dedicated training courses, winter schools and conference events on topics related to computational dosimetry. A list of such training and dissemination events in the past decade is given in Table 1.

With the progress in computational power that has taken place over the last few decades, the further development of Monte Carlo techniques, and the emerging use of machine learning in dosimetry, an increasing number of different codes are being used nowadays. Whilst this opens up new opportunities, they are, however, not for free, as quality assurance of the simulation results requires thorough training and experience along with efforts to establish a Monte Carlo "gold standard". It is important that users become fully aware of the need for uncertainty assessments of their simulation results, and that it is necessary to study the influence of variance of input data (e.g. geometry, cross sections, physics, etc.) on them, although this may involve considerable effort for standard Monte Carlo codes. The organization of intercomparison exercises and training courses therefore will stay an important task of WG 6 for the future. Furthermore, high-level intercomparisons will also be needed to ensure that important issues addressed by computational methods are treated using more than one code: experimental benchmarks are often missing in emerging areas, such as in high-energy fields or track structure simulations, so the codes may only be validated against each other. Overall, comparisons of results obtained using different approaches (e.g. condensed history vs. full track structure, Monte Carlo vs. analytical, or machine learning vs. Monte Carlo) will be needed to highlight differences and limitations, depending on the specific configuration of the simulation.

4. Outlook

Computational methods play an essential role in the area of radiation dosimetry. Some of the dosimetric concepts in radiation protection, such as the so-called protection quantities that are defined in anthropomorphic computational phantoms that cannot be constructed physically, can only be determined by computational methods. With ICRU currently revising the operational dose quantities to be also defined using anthropomorphic phantoms, computational dosimetry will play a key role in adjusting the radiation protection system to these changes, e.g. by evaluating the new conversion coefficients.

The rapid development of codes, and their flexibility and capability of providing solutions with detailed geometry descriptions, has made Monte Carlo simulation the tool of choice in radiation protection dosimetry as well as in medical applications. In radiation protection, the possibility of monitoring the dose received by an individual in real-time and as a personalized assessment might also soon be within reach. With the move towards personalized medicine, there is also an increasing importance of patient-specific dosimetry, for which computational dosimetry is an essential tool, where taking into account individual variability is making the computational task more complex.

The recent developments of numerical phantoms (mesh or NURBS phantoms) that no longer rely on a voxelized geometry, and also potentially permit adaptation of phantoms to the individual personal anatomy, in principle open the door towards individualized computational dosimetry that might even take into account motion. Practical realization of these is currently hampered by incompatibility with the approaches used for geometry description in most Monte Carlo codes, or by the computational effort involved. These obstacles can only in part be overcome by increased computational power or development of new variance reduction techniques. This opens the stage for methodologies based on machine learning, such as Convolutional Neural Networks, that would facilitate the use of personalized phantoms with realistic anatomies. They may also (within certain limits) replace current Monte Carlo simulations or be used for their acceleration to achieve truly real-time dose assessments.

Validation of such novel approaches will require intercomparisons with established Monte Carlo techniques, and assessments of the associated uncertainties. Developing a validation scheme for machine learning-based approaches by Monte Carlo techniques, and benchmarking of flexible numerical phantoms, will likely be two main extensions of the scope of WG 6 activities in the future. This will have to be accompanied by endeavors on the ongoing challenge of uncertainty assessment in computational dosimetry. Addressing this challenge involves critical assessment of the basic cross-section data that are used in the codes, particularly for novel medical applications involving new types of radionuclides or nanomaterials (Schuemann *et al* 2020), micro- and nanodosimetry, as well as novel workplace radiation environments. It will also involve developing means for sensitivity analysis of the simulation results on variation of the code input quantities, as well as the establishment of appropriate reference experiments as benchmarks.

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