Activities of EURADOS Working Group 6 “Computational Dosimetry”

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Abstract

The 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 WG6. 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 still ongoing exercises, 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 [1], [2], [3], [4].

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, WG6 strongly engages in collaborations with the other WGs that are focused on subject areas rather than techniques (Harmonization of Individual Monitoring, Environmental Dosimetry, Internal Dosimetry, Dosimetry in Radiotherapy, Retrospective Dosimetry, High-Energy Radiation Fields, Dosimetry in Medical Imaging). 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 WG6. However, other aspects and techniques, such as neutron spectra unfolding, play an important role as well. As a kind of 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 [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22].

In the past, 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. Within the still ongoing exercises on neutron spectra unfolding [20] and on assessing the uncertainty contribution of cross sections used as input parameters in track structure codes [21], 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.

1. Tasks within WG 6

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 that cover a certain scope of activities.

* 1. Neutron spectra unfolding

Task 1 on neutron spectra unfolding is dealing with 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 as the neutron energies to be considered spread over more than ten orders of magnitude [23]. As neutrons are indirectly ionizing particles, they are generally detected via their recoil protons produced in nuclear reactions. To cover the large relevant energy range, sets of so-called Bonner spheres (BS) are used, which feature a central sphere filled with 3He that is surrounded by spherical shells of polyethylene of different thickness and different inner and out coatings with suitable metals. By neutron interactions in the BS coating, their energy spectrum changes. The materials and geometries 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 (3H) by neutron capture of 3He.

A neutron field measurement thus consists of a set of count rates from the different BS 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 different tools [16]. 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 engages in a joint activity with EURADOS WG 11 High Energy Radiation Fields to prepare a training course on neutron spectra unfolding that is planned to take place in 2021.

Within the BS spectra (BSS) unfolding exercise organized by task group 1, participants were invited to unfold BSS data using a unfolding tool of their choice [20], information about the nature of the neutron field and calculated response matrices for idealized BSs. The BSS data consisted of the count rates and measurement uncertainties of a set of 13 BSs, that were calculated by the organizing team using Monte Carlo simulations of the experimental setups.

The following four scenarios for BSS measurements of neutron fields were considered: 1. at two points near a medical linear accelerator in a treatment room with a maze; 2. at 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 that were not involved in the simulation of the BSS 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.

* 1. 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 with 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 [21] and a joint code intercomparison exercise with WG7 “Internal dosimetry” on the dose enhancement around gold nanoparticles [22], [24], [25].

Within the two-step “uncertainty” exercise, the goal of the first step is the 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 for the discrepancies. The exercise was defined by a given simulation setup (source and ‘detector’ geometry, electron source energy spectrum) for which the microdosimetric specific energy spectrum or the nanodosimetric cluster size distributions were to be calculated [21]. The microdosimetric mean quantities calculated by the participants in this generally agreed well, 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 the task it was planned to implement a unique cross section data set in different track structure codes together with the estimated uncertainties and to transport these uncertainties through the simulation such as to get the uncertainty component of the simulation results that originates in the uncertainty of the cross sections. Given that the nanodosimetric radiation quantities obtained in the first part of the exercise exhibited so large discrepancies that these would require the uncertainty to be assumed as high as 100%, this part of the exercise is currently under redefinition.

In the joint code intercomparison exercise with WG7, the participants were to simulate the emitted electron spectrum and the microscopic dose deposition around gold nanoparticles for X-ray irradiation in an idealized simple geometry of a pencil beam of comparable diameter as the nanoparticle [22]. This artificial situation was meant to emphasize differences in interaction cross sections that would be expected particularly with respect to radiation interaction in gold, where the radiation interaction cross sections particularly of low-energetic electrons have not yet achieved the same level of evaluation as the cross sections for interactions in water. In the first analysis, the philosophy of the supplements to the ISO Guide to the expression of uncertainty in measurements was employed [26] 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 has 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 [24], [27].

* 1. Individual monitoring

Task 3 is concerned with Monte Carlo simulations for individual monitoring in radiation protection. As computational methods play an important role in assessing the operational quantities used in radiation protection, the task group is engaging in collaboration with WG2 Individual Monitoring to provide training course related to the use of Monte Carlo techniques for this purpose. In addition, the task group has also been contributing to a cross-WG activity on development of a comment on the imminent change in radiation protection quantities proposed by the International Commission on Radiation Units and Measurements [28]. Two recent major research activities conducted by this task group have been related to skin dosimetry and retrospective dosimetry. With respect to skin dosimetry, the issue is an improved skin model as the voxel size in the presently used numerical ICRP phantoms for the standard male and female [29] 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 layer of different thickness depending on the location on the body [30], which may not be sufficient in particular for stochastic effects or very inhomogeneous exposure such as from “hot” (radioactive) particles. The activities on retrospective dosimetry (performed in collaboration with WG10 “Retrospective Dosimetry”) 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 [31], [32], the development of conversion algorithms from absorbed dose-related signals measured from mobile phone components to organ doses for use in emergency scenarios and the generation of a data base of conversion coefficients for the most relevant exposure sources such as (at present) 137Cs, 60Co and 192Ir radionuclides as well as 100 keV X-rays for different irradiation geometries.

* 1. In-vivo dosimetry

Task 4 on in-vivo dosimetry has been terminated recently after a long record of joint activities in collaboration with WG7 Internal Dosimetry encompassing 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 [9], [10], [11], [14], [15], [17], [18], [33], [34], [35], [36]. In the most recent intercomparison on the determination of the activity of the nuclear fall-out product 241Am in the human skull, intercomparisons of Monte Carlo simulations were performed for three levels of complexity of the simulation problem [17], [18]. 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 [17]. The intermediate complexity problem encompassed simulation of a real detector where the relevant material parameters and dimension 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 [18]. All three intercomparison parts were addressed by 15 to 16 participants, mostly using the MCNPX code, but there were also results produced using other codes, namely EGS4, Geant4 and VMC.

* 1. Linac modelling

Task 5 has been conducting an intercomparison exercise on the design and dosimetry assessment of a linear accelerator (LINAC) facility [4], [19]. In the first part of the exercise, participants were 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) based on information on the LINAC head geometry and material composition and 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 of the six participants in the exercise who used four different Monte Carlo codes (Geant4, EGSnrc, Tripoli 4 and MCNPX). 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 the first task to be solved was underdetermined such that different electron beam parameters could equally well reproduce the measurements in a simple homogeneous water phantom, of which some led to significant discrepancies for the cases with heterogeneities [19]. The simulation set-up used in the exercise has been adopted by the international Geant4 collaboration [37], [38] as an advanced example for self-training of new users of the code system.

* 1. Voxel phantoms

Task 6 is concerned with the implementation of voxel phantoms in Monte Carlo simulation for assessing radiation protection quantities (organ doses, effective dose) where in the past significant contributions were made to intercomparisons in in vivo dosimetry (in collaboration with Task 4 and WG7) [9], [10], [34], [35]. Another important activity has been 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 to test the participants capability of properly implementing the ICRP reference computational phantoms [29] in Monte Carlo simulations to calculate organ doses (and from these equivalent doses and the radiation protection quantity effective dose). The considered exposure scenarios were designed such that cases of occupational, accidental and medical exposure were covered as well as several radiation types (photons, neutrons, electrons).

The occupational exposure scenarios were irradiation by a 60Co photon point source or a monoenergetic 10 keV neutron point source, both in AP irradiation geometry with the source in front of the exposed human body at 125 cm from the bottom and 100 cm from the chest. The former is the easiest scenario that was addressed by 17 participants, while for the latter only one solution was received.

The accidental exposure scenarios were ground contamination with the 241Am radionuclide within a circle of 2 m radius with the phantom standing in the center, that attracted 3 participants, and exposure in a room where the air is contaminated with the β emitting radionuclide 16N. Here part of the exposure would be from inhaled radionuclides in the lung and 6 participants delivered solutions.

For medical scenarios, an idealized typical X-ray examination of the chest in AP geometry (irradiation from the front) and of the abdomen in PA geometry (irradiation from the back) was chosen. Here, the eight participants submitting solutions had to determine the location of the source point relative to the phantom co-ordinate system for the given target organ to be screened, and to 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 referring to internal exposure that could occur in occupational, accidental and medical situations. Here the task was to evaluate quantities relevant for dose assessment for the artificial case of monoenergetic photons or electrons emitted within certain source organs and for the radiation 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 such as to assure 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 to apply the method proposed in ICRP Publication 116 for determining the doses to red bone marrow and bone surface or to describe any deviating bone dosimetry method in detail.

* 1. 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 had been an important activity [39], [40], [41]. Later on, Bonner sphere responses for high energy neutrons have been modelled and benchmarked with measurements [42]. The discrepancies due to the different models employed in the various high energy codes to generate neutron-scattering cross-section data for the whole energy domain from MeV to GeV remain an ongoing challenge. Currently a literature review is conducted to compile a summary of the capabilities of the codes in use and the definition of intercomparison exercises to assess the implementation of the models in the codes are in preparation.

* 1. WG 6 Strategy (formerly uncertainty and sensitivity assessment)

Originally established for addressing the overarching topic of uncertainties in computational dosimetry where the comprehensive QUADOS exercise had been conducted in the past [5], [6], [7], [8], task 8 is presently concerned with the steering and strategy of the working group. A major activity in the past has been providing input to the Strategic Research Agenda of EURADOS [1], [2].

* 1. Nuclear medicine

Task 9 engages together with WG 12 “Dosimetry in medical imaging” and WG7 “Internal Dosimetry” in a collaboration with the European Association of Nuclear Medicine (EANM) on dosimetric issues related to diagnostic and therapeutic nuclear medicine such as the dose received by cares/comforters of patients receiving nuclear medicine treatment or members of the public from persons that underwent a nuclear diagnostic procedure. Currently the research is focused on the development of a computational approach for the determination of external dose rates received by other person from nuclear medicine patients for a set of specific geometries. A major challenge encountered in this context are related to the biokinetics of the radionuclides in the human body.

* 1. Radiotherapy and radiation diagnostics

Task 10 radiotherapy and radiation diagnostics has been 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 out-of-field 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 by 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 are a major concern and data analysis of experimental measurements often require auxiliary information from radiation transport simulations. Another 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 WG7 “Internal Dosimetry” and WG12 “Dosimetry in Medical Imaging” on dosimetry issues of emerging radiopharmaceuticals (e.g. Ga-68, Lu-177)

1. Education and training activities

**Table 1** Training courses and workshops delivered by EURADOS WG6 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 |

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 is to be attributed to the code users [7], [8]. In contrast to key comparisons in metrology, where the technical protocol is agreed in advance by the participants who have already a track record of experience in the measurements to be performed, the intercomparisons in computational dosimetry have a different character. While the exercises are prepared by experts in the field and methodology, many participants are often less experienced code users, often early stage researchers, that may be easily tempted and mislead by the ease many further developed Monte Carlo codes offer nowadays to believe that, e.g. small standard deviation would be a sign of low uncertainties or that dividing results by the number of primary particles would be proper normalization. Apart from annoying aspects that complicate data analysis, such as results not reported using the provided templates and/or with different binning, the intercomparisons often reveal naivety and conceptual misunderstandings of the simulation problem as well as a lack of awareness that simulation results need to be checked for plausibility, such as 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 was deviating 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 being significant [17], [18], [24].

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 [21], [43]. 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 demonstrates a level awareness that may not be common within the community of code users.

Therefore, like the other working groups within EURADOS, WG6 also contributes to EURADOS’ mission of promoting harmonization and good practice in radiation dosimetry by organizing and contributing to education and training events [3] such as dedicated training courses, winter schools and conference events on topic 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 computer power, the further development of Monte Carlo techniques and the emerging use of machine learning in dosimetry, more and more different codes are being used. This opens up new opportunities that 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 of uncertainty assessment for simulation results and that it is necessary to study the influence of variance of input data (geometry, cross sections, physics, etc.) on the simulation results, 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 WG6 for the future. Furthermore, also high-level intercomparisons will be needed to assure that important issues addressed by computational methods are treated using more than one code. As often experimental benchmarks are missing in emerging areas such as in high-energy fields or track structure simulations, the codes may only be validated against each other. Overall, comparison of results obtained using different approaches (e.g. condensed history vs. full track structure or Monte Carlo vs. analytical and machine learning vs. Monte Carlo) will be needed to highlight differences and limitations, also depending on the specific configuration of the simulation.

1. 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, which 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 entirely 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 in a personalized assessment might 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 that no longer rely on a voxelized geometry but rather permit adaptation of phantoms to the individual personal anatomy (mesh or NURBS phantoms), in principle, open the door towards individualized computational dosimetry that might even take into account motion. Practical realization 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 computer 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 be 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 assessment.

Validation of such novel approaches will require intercomparisons with established Monte Carlo techniques and assessment 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 WG6 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 [44], 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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