European Commission

Radiation Protection

No 197

EU Scientific Seminar 2021

Advances/Innovations in individual dosimetry

Energy

ISSN 2315-2826

Luxembourg: Publications Office of the European Union, 2022

Print	ISBN 978-92-76-59364-5	ISSN 1681-6803	doi:10.2833/084473	MJ-XA-22-001-EN-C
PDF	ISBN 978-92-76-59363-8	ISSN 2315-2826	doi:10.2833/17425	MJ-XA-22-001-EN-N

EUROPEAN COMMISSION

RADIATION PROTECTION N° 197

EU Scientific Seminar 2021

Advances/Innovations in individual dosimetry

Proceedings of a scientific seminar held via WebEx on 9 November 2021

Working Party on Research Implications on Health and Safety Standards of the Article 31 Group of Experts

Directorate-General for Energy

Directorate D — Nuclear Energy, Safety and ITER

Unit D3 — Radiation Protection and Nuclear Safety

2022

Foreword

Luxembourg, October 2022

The European Commission organises every year, in cooperation with the Group of Experts referred to in Article 31 of the Euratom Treaty, a Scientific Seminar on emerging issues in Radiation Protection – generally addressing new research findings with potential policy and/or regulatory implications. Leading scientists are invited to present the status of scientific knowledge in the selected topic. Based on the outcome of the Scientific Seminar, the Group of Experts referred to in Article 31 of the Euratom Treaty may recommend research, regulatory or legislative initiatives. The European Commission takes into account the conclusions of the Experts when setting up its radiation protection programme. The Experts' conclusions are valuable input to the process of reviewing and potentially revising European radiation protection legislation and may assist in the implementation of Council Directive 2013/59/Euratom (Basic Safety Standards Directive).

In November 2021, the EU Scientific Seminar covered the issue *Advances/Innovations in individual dosimetry*. Internationally renowned scientists presented the following topics:

- New dosimetry techniques – an overview (including eye-lens dosimetry)
- Aircrew and space crew dosimetry
- Dosimetry in pulsed fields and mixed fields (including radiation protection of personnel in proton therapy facilities)
- Computational dosimetry and use of Artificial Intelligence (AI).

The presentations were followed by a round table discussion, in which the speakers and additional invited experts discussed potential *policy implications and research needs* under the key areas of:

- ICRU/ICRP report on the new operational quantities in radiation protection
- Impacts of the ICRU/ICRP report relevant to dosimetry.

The Group of Experts discussed this information and drew conclusions that are relevant for consideration by the European Commission and other international bodies.

Contents

Foreword 3
Contents 4
New dosimetric techniques: an overview, including eye lens dosimetry 6
Abstract 6
1. State of the art of passive dosimetry 6
2. Active personal dosemeters 7
3. Eye lens dosimetry 8
4. Computational dosimetry 9
5. Conclusion 10
6. References 10
Aircrew and Space Crew Dosimetry 12
Abstract 12
1. Introduction 12
2. Aircrew Dosimetry 13
    2.1 Aircrew Exposure in Germany 13
    2.2 EURADOS Intercomparison Study – Galactic Cosmic Radiation 14
    2.3 EURADOS Intercomparison Study – Solar Cosmic Radiation 15
3. Space Crew Dosimetry 17
    3.1 Recent ICRP Activities 17
    3.2 Recent NASA Activities 18
4. References 20
Dosimetry in pulsed fields and mixed fields (including radiation protection of personnel in proton therapy facilities) 22
Abstract 22
1. Introduction 22
2. Definition of pulsed fields 23
3. The LUPIN REM-counter 25
4. Experimental activity performed by the EURADOS WG11 27
    4.1 Experiment at the Helmholtz-Zentrum Berlin (HZB) 28
    4.2 Experiment at Maastro Pulsed Proton Therapy centre 31
5. Conclusions 35
6. References 35
Computational dosimetry and use of artificial intelligence (AI) 37
Abstract 37
1. Introduction 37
2. Monte Carlo Radiation Transport Simulation 38
3. Artificial Intelligence and Machine Learning 39
4. Challenges and caveats 42

4.1 Challenges for AI methods in computational dosimetry 42
4.2 State of the Art in Computational Dosimetry 43
5. Conclusions 46
6. References 47
Roundtable presentation - ICRU Report 95: Operational Quantities for External Radiation Exposure 54
Roundtable presentation - New Operational Quantities for External Radiation Exposure: EURADOS Impact Evaluation 57
Context 57
Benefits of New Quantities 57
Main conclusions 58
Devices (Instruments and Dosemeters) 58
Possible adaptations 58
Measurement Uncertainties 58
Spreading of Costs 59
International standards 59
Calibration Labs: Changed practices 59
Reduced Doses at Medical/ Diagnostic X-ray Energies 59
Higher Energies 60
Recommendations 60
Summary 61
1. Introduction 61
2. The Article 31 Group of Experts and the rationale of the scientific seminars 61
3. Key highlights of the presentations at the Scientific Seminar on Advances/Innovations in individual dosimetry 62
4. Summary of the roundtable discussion: policy implications and research needs 67
Conclusions 69

New dosimetric techniques: an overview, including eye lens dosimetry

Filip Vanhavere[1]

SCK CEN, Belgian Nuclear Research Centre

Abstract

This paper is giving a short overview of the state-of-the-art of personal dosimetry. It will highlight the new developments and areas where improvement is still needed. The problem of eye lens dosimetry will also be discussed shortly, and possible future evolutions in personal dosimetry through computational dosimetry will be discussed.

1. State of the art of passive dosimetry

Individual monitoring of workers exposed to external ionizing radiation is essential to allow application of the ALARA principle and to show compliance with the regulatory dose limits [1].

Most legal dosimetry is done with passive dosemeters, which are analysed after the wearing period in an approved/accredited laboratory. Such dosemeters do not give alarms in high exposure situations, and the results are available only after one or several weeks. Not much evolution has taken place in personal dosimetry in the last 50 years. The method of dosimetry itself has not changed. It is still a point measurement on the body of the worker, with a device that needs to be sent to a laboratory for analysis. The techniques have evolved, from film dosemeters over thermoluminescent dosimetry methods to optically stimulated luminescence. This has improved the performance of the dosemeters on several points. The energy and angular dependence has improved by the use of near tissue equivalent dosemeters like LiF and BeO, and by the use of advanced algorithms for non-tissue equivalent dosemeters. Fading is also less of a problem in most dosemeters used nowadays, and the sensitivity has increased, leading to a reporting level of 50 µSv for monthly exchange.

There is a trend that dosimetry services are increasing in size, with a development towards larger, more international services, and a decrease of local smaller services. Accreditation and approval is more and more mandatory, which also leads to better quality assurance and traceability of the services.

Still, overall, large uncertainties exist in personal dosimetry. According to ICRP 75 [2], the overall uncertainty at 95% confidence level in the estimation of the effective dose using personal dosemeters may well be in a factor of 1.5 in both directions for doses around the

[1] Corresponding author: Filip Vanhavere, SCK CEN, Belgian Nuclear Research Centre, filip.vanhavere@sckcen.be

dose limit, and a factor of 2 for lower doses. This results in the so called "trumpet curves", which is used among others to evaluate the performance of dosimetry services in intercomparisons [3]. The accepted uncertainty is even higher for neutron dosemeters.

These allowed uncertainties for personal dosemeters are large because the range of energies and angles encountered in real workplace fields are wide. Even though improvements have been made, there still do not exist small and light weight personal dosimeters with perfect response for all energies and angles that would allow significantly lower uncertainty limits.

To get an idea on how well the presently used passive personal dosemeters are performing, it is interesting to look at the results of large international intercomparisons. EURADOS is organising such periodic intercomparisons, where the performance is judged comparing to the trumpet curves. In the intercomparison of 2012 for whole body dosemeters [4], 87 dosimetry services participated, mostly from Europe. From the 1400 irradiated dosemeters, only 6 % where outside the trumpet curves. The average response from all dosemeters compared to the reference value was 0.98. The 90 % of all services fulfilled the ISO 14142 [3] criteria to have maximum 2 outliers. Therefore, it can be stated that the large majority of the dosemeters in the field have no problem in satisfying the trumpet curve criteria.

It must be realised however, that in such intercomparisons only few mixed fields are used with no other factors are taken into account like environmental influences, high energy beams, high irradiation angles or workplace fields.

The situation is worse when you look at the results from the extremity dosemeters, e.g. from the intercomparison of 2009 [5]. The results for gamma's were relatively good, but for lower beta's (like the ones where Kr-85 is used) 65 % of the results were outside the trumpet curve. In neutron dosemeter intercomparisons, the results are even much worse [6], with many services requiring workplace field information to be able to estimate the doses received.

Therefore, there is certainly still room for improvement in the use of the personal dosemeters. Even though there is large uncertainty to get from a dosemeter result to the estimation of the effective dose [2] and from this value to the risks for stochastic effects, any improvement in the performance of a dosemeter would greatly enhance the reliability of the dosemeters.

In the last years, one new technological development has come on the market. The hybrid dosemeters, like the Instadose, which are still passive (no alarms), but do not require periodic returning to the dosimetric service. The read-out is done in the dosimeter itself, which has a long standalone battery life. They have no display, but their results can be consulted, whenever needed, via an intermediate device such as tablet, phone or pc. Of course, the use of such dosemeters still needs the involvement of an approved dosimetry service for quality control, periodic calibration and background subtraction. One also has to be careful with the possible problems due to temperature fluctuations.

2. Active personal dosemeters

Active personal dosemeters (APD) are also widely used, although mostly only for ALARA purposes or for specific exposure situations. Especially in the nuclear industry they are used extensively, but not so much in medical applications. The APDs have the clear advantage that they give feedback to the exposed workers, and as such the workers also pay more attention to their APD. The use of the APDs will continue to increase, and many different types are now available. Through technological developments, the active dosemeters are dosimetrically and technically at least equivalent to passive dosemeters. Still, they are mostly used just as ALARA dosemeters, while a passive dosemeter is used for the dose of record to check compliance with the dose limits. The reason is on one part their higher cost, and on the other hand that one still needs an approved dosimetry service (e.g. for quality control, periodic calibrations and background subtraction) to operate a legal APD system.

It must also be realised that not all APDs are suited for all radiation fields. Many of the APDs perform badly for low X-ray energies (<60 keV) like encountered in interventional fields in hospitals, and for low beta energies. Compared to passive dosemeters, APDs will also have limitations when they are used in pulsed fields. And just as passive dosemeters, the APDs only give a point measurement on the body, which is a big limitation in inhomogeneous fields.

3. Eye lens dosimetry

In its statement on tissue reactions from 2011, the International Commission on Radiological Protection (ICRP) has reviewed its recommendation about the equivalent dose limit for the lens of the eye [7]. The new recommendation is: "For occupational exposure in planned exposure situations the Commission now recommends an equivalent dose limit for the lens of the eye of 20 mSv in a year, averaged over defined periods of 5 years, with no single year exceeding 50 mSv". The previous limit for workers, set to protect against non-stochastic effects, was of 150 mSv in a year. This new limit is challenging in terms of radiation protection for some radiation workers (like in interventional procedures in hospitals) but also in terms of specific dosimetry, which became necessary.

The protection quantity for the eye lens is the equivalent dose to the eye lens, H_{lens}. In practice, this is approximated by the operational quantity, $H_p(3)$, the equivalent dose at 3 mm depth. Although this quantity was new a few years ago, in the meantime several $H_p(3)$ dosemeters are available on the market. Most of these dosemeters work with thermoluminescent detectors based on LiF. Also, for these dosemeters, an evaluation of their performance has been studied through a EURADOS intercomparison [8]. In the results of the 2015 intercomparison, we see that most dosemeters perform very well in relevant reference fields. Therefore, the measurements capabilities are not really the problem with eye lens dosimetry.

The real problem is that workers are very reluctant to wear an eye lens dosemeter because they are not very practical. In theory, such dosemeter should be worn close to the eye, in contact with the skin (to account for the backscatter radiation), faced to the radiation source, and preferably behind the lead glasses [9]. It can be easily understood that this causes difficulties in practice. There are different international initiatives (ISO, IRPA, IAEA,..) that are focused on the practical consequences of this reduced eye lens limit.

According to the BSS [1], systematic monitoring is obliged for category A of exposed workers, so as soon as 3/10th of the relevant dose limit can be reached. This means that if 6 mSv can be reached in consecutive years, monitoring should be obligatory. And such doses can quite easily be reached by interventional operators in hospitals, depending on the level of personal protection they use. An easy way to know if monitoring is needed, is setting up a series of confirmatory measurements [9].

As routine monitoring is not always very practical, several other ways of estimating the eye lens dose have been proposed. Some studies suggest estimating the dose to the lens of the eye from a well-placed dosemeter at collar level. In general, this might be acceptable in homogeneous fields with higher energy radiation, but this cannot be recommended in other fields. Certainly, this cannot be used when the whole body dosemeter is placed under the lead apron. But even if a collar dosemeter is well placed, the correction factor to go from the collar dose to the eye lens dose is very dependent on the type of procedure, personal habits, the exact place of the dosemeter and the protection measures taken. Literature [10] shows that there can be a factor of near 10 uncertainty introduced if this practice is applied. So this system can give good indication of when dedicated eye dosimetry is needed, but it is not a good measurement practice.

When using protective lead glasses, it gets very difficult to measure the real eye lens doses. Also here, the solution is measuring outside the lead glasses, and using a correction factor (a DRF, dose reduction factor). Looking at the literature [11] one can see that there are many influencing factors to determine such DRFs. Especially the type of glasses (model, fitting, geometry) has a big influence on their protection capabilities. It is also clear that lead glasses do not offer complete protection, thus monitoring may still be needed, even if such glasses are used. In general, one can say that for any type of lead glasses a DRF of 2 can be used, and a factor of 3 can be considered for better designs [11].

In conclusion, although the measurement capabilities are available for eye lens dosimetry, more practical guidance and solutions are needed to improve the accuracy of measurements and to come to proper monitoring of the eye lens doses.

4. Computational dosimetry

Whenever using physical dosemeters, many practical problems will continue to exist for personal dosimetry. A large part of the dosemeters get lost and the reluctance of many workers to wear one or more dosemeters (ring, eye lens…) is very big.

In an attempt of reinventing dosimetry by using the modern evolutions in Monte Carlo simulations, artificial intelligence and computer vision, the PODIUM project was set up. PODIUM was a short feasibility project, funded by the EC under the CONCERT programme, and stands for Personal On-line DosImetry Using computational Methods [12].

The objective of the PODIUM project was to improve personal dosimetry by an innovative approach: the development of an online dosimetry application based on computer simulations without the use of physical dosemeters. Operational quantities, protection quantities and radiosensitive organ doses (e.g. eye lens, brain, heart, extremities) could be calculated based on the use of modern technology such as personal tracking devices, flexible individualized phantoms and scanning of geometry set-up. When combined with fast simulation codes, the aim was to perform personal dosimetry in real-time.

We applied and validated the methodology for two situations where improvements in dosimetry are urgently needed: neutron workplaces and interventional radiology. For that purpose, the spatio-temporal radiation field, including its energy and angular distribution, needed to be known. We use input from dose monitors in the neutron workplace and radiation dose structured reports (RDSR) from the X-ray machine used in interventional radiology; and we capture real movements of exposed workers and transfer them to the calculation application.

This feasibility study gave good results. Several validation and test measurements were done in different hospitals, and in two workplace fields with significant neutron exposure. Personal doses could be calculated within acceptable simulation times, just based on captured movements of the workers and information on the radiation fields. These doses agreed with the results from physical dosemeters within the uncertainties that are acceptable in personal dosimetry.

The PODIUM project was just the first step towards such novel dosimetry. This PODIUM dosimetry method can overcome the problems that arise from the use of current passive and active point dosemeters. These simulation results can also be used to visualize the radiation field in near real time. This will increase awareness of radiation protection among workers and will improve the application of the ALARA principle, and it can also be used in training modules. The use of neural networks and big data will help in further reducing simulation time, making real time simulations and dosimetry without physical dosemeters possible in the near future.

5. Conclusion

Dosimetry for compliance with legal requirements is mostly performed with passive point dosemeters, which are analysed after the wearing period in an accredited lab. Active personal dosemeters (APD) are also widely used, although mainly for ALARA purposes or for specific exposure situations. Eye lens dosimetry is also available, but although the measurement capabilities are available, more practical guidance and solutions are needed to come to proper monitoring of the eye lens doses. The acceptable uncertainties for personal dosemeters are large because the range of energies and angles encountered in real workplace fields are wide. In the future, computational methods might form part of the solution to improve personal dosimetry.

6. References

[1]. Council of the European Union. *Council Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom*. OJ of the EU. 2014; L13:1-73.

[2]. International Commission on Radiological Protection, *General principles for the radiation protection of workers*, ICRP publication 75. Ann. ICRP 27(1), 1997.

[3]. International Organization for Standardization, *Criteria and performance limits for the periodic evaluation of dosimetry services*. ISO 14146, 2018.

[4]. McWhan, A. F. et al., *EURADOS Intercomparison 2012 for Whole Body Dosemeters in Photon Fields,* EURADOS Report 2015-02.

[5]. Grimbergen, T.W.M. et al., *EURADOS Intercomparison 2009 for Extremity Dosemeters in Photon and Beta Fields,* EURADOS Report 2013-03.

[6]. Mayer, S. et al., *EURADOS Intercomparison IC2017n for Neutron Dosemeters*, EURADOS report 2021-06.

[7]. International Commission on Radiological Protection, *ICRP statement on tissue reactions and early and late effects of radiation in normal tissues and organs—threshold doses for tissue reactions in a radiation protection context*. ICRP Publication 118, Ann. ICRP 41(1–2) 2012.

[8]. Clairand, I. et al., *First eurados intercomparison exercise of eye lens dosemeters for medical applications*, Radiation Protection Dosimetry, Volume 170, Issue 1-4, 21 – 261, 2016.

[9]. International Standard Organisation, *Radiological protection—Procedures for Monitoring the Dose to the Lens of the eye, the Skin and the Extremities,* ISO 2015 15382:2015.

[10]. Farah, J. et al., *A correlation study of eye lens dose and personal dose equivalent for interventional cardiologists,* Radiation Protection Dosimetry 157(4), pp. 561-569, 2013.

[11]. Martin, C.J., *Eye Lens Dosimetry for Fluoroscopically Guided Clinical Procedures: Practical Approaches to Protection and Dose Monitoring*, Radiation Protection Dosimetry 169 (1-4), pp. 286–291, 2016.

[12]. Abdelrahman, M. et al., *First steps towards online personal dosimetry using computational methods in interventional radiology: Operator's position tracking and simulation input generation*, Radiation Physics and Chemistry, 171, 108702, 2020.

Aircrew and Space Crew Dosimetry

Werner Rühm[2]

Helmholtz Center Munich, Institute for Radiation Medicine, 85764 Neuherberg, Germany

Abstract

Following recommendations of the International Commission on Radiological Protection (ICRP) aircrew is regularly monitored in many countries for their exposure to cosmic radiation. Although there is no general approach of dose monitoring in space, exposure of astronauts to cosmic radiation is currently attracting increasing interest. In this paper, results from two studies of the European Radiation Dosimetry Group (EURADOS) are presented. In these studies, the performance of computer codes used to quantify flight route doses to aircrew from galactic cosmic radiation and from solar particle events was compared. The results indicate reasonable agreement within ±30 % for route doses from galactic cosmic radiation, while the agreement was only ±90 % for route doses from solar particle events. As for radiation protection in space, the ICRP has recently established a task group dealing with risk and dose assessment for radiological protection of astronauts. The goals of this task group are described, as well as recent developments initiated by NASA to prepare for deep exploratory space missions during which radiation doses will become significant and may exceed 600 mSv.

1. Introduction

In 1991, the International Commission on Radiological Protection (ICRP) recommended for the first time that "*there should be a requirement to include exposures to natural sources as part of occupational exposure*". Among the natural radiation sources listed by the ICRP were radon, natural radionuclides, and cosmic radiation exposure during operation of jet aircraft and space flight. As for operation of jet aircraft, the Commission specified that this "*will relate principally to the aircraft crew, but attention should also be paid to groups such as couriers who fly more often than other passengers*" (ICRP 1991). In contrast, in this publication space flight was not discussed further because it related only to very few individuals.

In the most recent general recommendations of ICRP published in 2007 (ICRP 2007), radiation exposures in space were again only briefly touched. Specifically, it was emphasized that the "*exceptional cases of cosmic radiation exposures, such as exposure in space travel, where doses may be significant and some type of control warranted, should be dealt with separately, taking into account the special type of situations that can give rise to this type of exposure*". However, more recently the topic of radiation protection of

[2] Corresponding author: Werner Rühm, Helmholtz Center Munich, Ingolstädter Landstr. 1, 85764 Neuherberg, werner.ruehm@helmholtz-muenchen.de

space crew became more popular, probably due to increasing space activities of various countries, plans for long-term missions to Mars, and the emerging field of space tourism.

In chapter 2 of this paper, some experience that has been made in monitoring aircrew in Europe is described, while chapter 3 highlights more recent international activities with respect to radiation protection of astronauts in space.

2. Aircrew Dosimetry

Motivated by ICRP Publication 60 (ICRP 1991), protection against the exposure to natural sources of ionising radiation became increasingly important worldwide. For example, in 1996 the Council of the European Union adopted the Basic Safety Standards Directive, a Directive dealing also with protection against significantly increased exposure by natural radiation (EU Directive 96/29 EURATOM). This Directive required, among other issues, Member States of the European Union to transpose the requirements for protection of aircrew against cosmic radiation into national legislation. Consequently and as an example, in 2001 the German radiation protection ordinance required aircrew members to be monitored if they are employed by an airline and if the expected annual effective dose is greater than 1 mSv (StrlSchV 2001). As a result, since August 2003 airlines in Germany must quantify radiation doses to their aircrew and report the monthly effective doses due to exposure to cosmic radiation to the German dose registry.

Dose assessment of aircrew is a difficult task because the radiation field of secondary cosmic radiation in the atmosphere is complicated. In fact, in the atmosphere primary cosmic radiation – either the galactic cosmic radiation (GCR) or the solar cosmic radiation (SCR) – produces a shower of secondary particles including protons, neutrons, electrons, positrons, photons, pions, etc., with energies spanning a vast range from meV to more than GeV. The radiation field finally produced is further complicated as it depends on altitude (because of the interplay between particle production in and shielding by the atmosphere), geographic position (i.e., longitude and latitude, due to the shielding effect of the geomagnetic field), and time (due to variations of the solar activity during a Solar Cycle). Unfortunately, it is very difficult, if not impossible, to monitor radiation doses from all the particles comprising the secondary cosmic radiation in the atmosphere with a simple, manageable dosemeter. Consequently, individual dosimetry of aircrew is realised by means of computer codes, which allow calculation of flight route doses for any flight profile and any time during a Solar Cycle. One such code - among a number of codes on the market - is the EPCARD code (European Program Package for the Calculation of Aviation Route Doses) developed at the Helmholtz Center Munich, Germany (Schraube et al., 2002; Mares et al., 2009).

2.1 Aircrew Exposure in Germany

When aircrew was first monitored in Germany (in August 2003, see above), about 30,000 individuals met the condition for being included in the monitoring programme. The following years saw a continuous increase in the number of monitored individuals, and in 2018 the airlines reported doses of about 42,000 aircrew members to the German dose registry. Interestingly, in Germany aircrew is among the professions with the highest annual effective doses: typically, mean annual effective doses of German aircrew are about 2 mSv, with slight variations due to variations in solar activity during a solar cycle. Given this, it is not surprising that in terms of annual collective effective dose (for which the number of individuals is multiplied by their mean annual effective dose) aircrew is the most important occupation in Germany. Specifically, annual collective effective dose of aircrew was 60 person Sv in 2003, while it increased to 89 person Sv in 2018 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2019).

2.2 EURADOS Intercomparison Study – Galactic Cosmic Radiation

In 2012, the European Radiation Dosimetry Group (EURADOS) published the results of a study where the performance of 11 computer codes developed for the assessment of flight route doses was compared (Bottollier-Depois et al., 2012a; Bottollier-Depois et al., 2012b). Study participants had to calculate radiation doses for 23 different flight routes including for example transatlantic flights, routes across the North Pole, and routes on the southern hemisphere. Two departure times were chosen, one in August 2000 close to solar maximum of Solar Cycle 23, and the other in September 2007 close to solar minimum. Results were reported in terms of route effective doses and/or route ambient dose equivalents.

Figure 1 shows as an example the route effective doses as reported by the study participants for the 23 chosen flights. For example, for September 2007 flight no. 1 (which was from Singapore to Sydney, Australia) resulted in a median route dose of about 20 µSv with reported values ranging from about 10 to 25 µSv, while flight no. 23 (which was from Singapore to Newark, US) resulted in a median route dose of about 95 µSv with reported values ranging from 77 to 105 µSv.

Figure 2 shows the frequency distribution of the relative deviation of the results reported for all flight routes and both departure times (August 2000 or September 2007). Obviously, the vast majority of reported dose values were within ±20 % from the median, and only few dose values differed by more than ±30 % from the median. Specifically, only "*one code provided systematically lower dose and dose rate values (up to –40 %), while another code showed a few dose and dose rate values that were higher by some +30 %*" (Bottollier-Depois et al., 2012a; Bottollier-Depois et al., 2012b). The study authors concluded that "*the overall agreement between codes was better than ±20 % from the median*". Because most of the codes had been validated experimentally before with an agreement between measured and calculated doses better than ±20 % (Lindborg et al., 2004a; Lindborg et al., 2004b), radiation dose monitoring of aircrew with dedicated computer codes (which can be considered as digital dosemeters) can be considered sufficient for radiation protection purposes. The results of this study were simultaneously published as EC Report Radiation Protection 173 (Bottollier-Depois et al., 2012a) and EURADOS Report 2012-03 (Bottollier-Depois et al., 2012b).

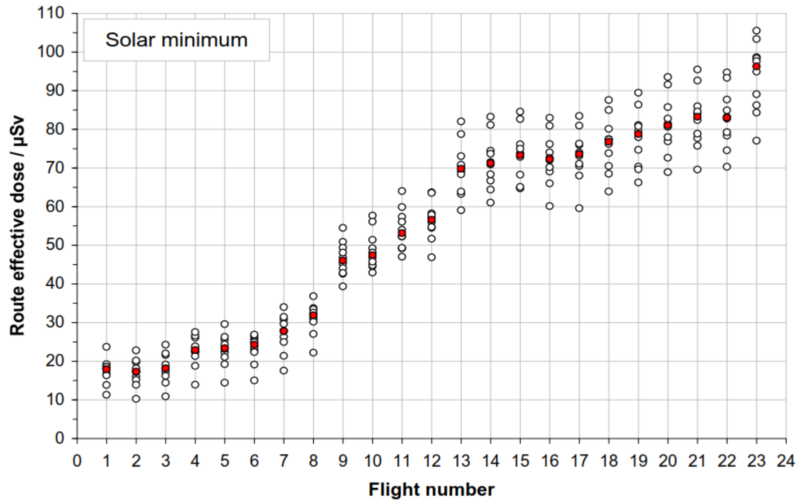

Figure 1. *Route effective doses calculated by 11 computer codes for 23 flights and September 2007 (figure taken from Bottollier-Depois et al., 2012a; Bottollier-Depois et al., 2012b).*

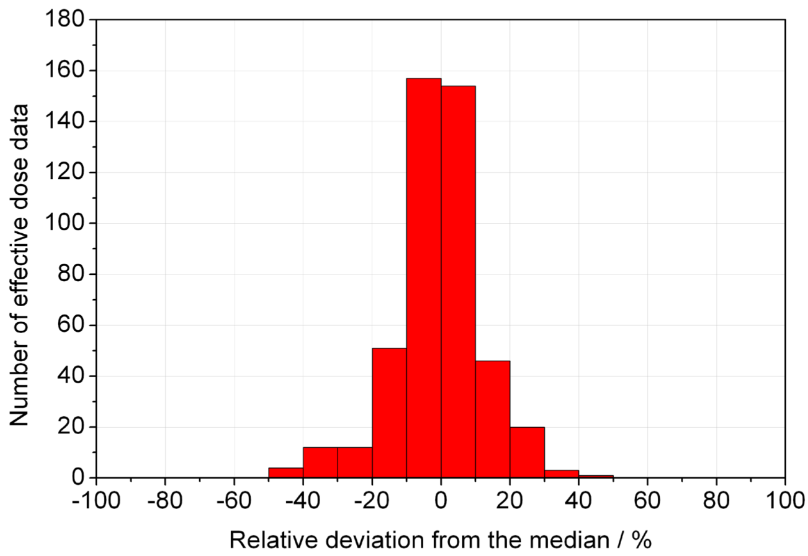

Figure 2. *Frequency distribution of relative deviation from the median of route effective doses calculated by 11 computer codes for 23 flights and September 2007 (figure taken from Bottollier-Depois et al., 2012a; Bottollier-Depois et al., 2012b).*

2.3 EURADOS Intercomparison Study – Solar Cosmic Radiation

In a follow-up study, EURADOS investigated the performance of nine computer codes that allowed calculation of flight route doses during solar particle events (SPEs) due to large eruptions on the Sun leading to ground level enhancements (GLEs) of secondary cosmic radiation close to the surface of the Earth. Some of these codes had been included in the previous study because they are routinely used to asses flight route doses from galactic cosmic radiation, while others were specifically developed to assess radiation doses during an SPE. Three flight routes were selected: San Francisco – Paris (a transatlantic flight), Chicago – Beijing (a flight across the North Pole), and Sydney – Johannesburg (a route on the southern hemisphere). Study participants were given two tasks: a) to assess flight doses on September 29, 1989, due to the galactic cosmic radiation and due to GLE42 for which a simplified primary particle spectrum impinging the atmosphere was given; and b) to assess flight doses on January 20, 2005, when GLE 69 occurred; in this case no primary particle spectrum was given but instead the participants were asked to deduce a primary particle spectrum with information from the literature. This task was significantly more demanding than the assessment of flight doses from galactic cosmic radiation or GLE42 because the dose rate resulting from GLE69 showed a significant heterogeneity leading to effective dose rates at an altitude of 10.5 km that differed several orders of magnitude depending on latitude and longitude.

As expected, flight route doses from the GCR component during GLE42 estimated by the codes were quite reliable, and within ±30 % from the median. Similarly, most of the flight route doses calculated for GLE42 were within ±25 % from the median. A similar result was obtained for route doses from the GCR component during GLE69 (Figure 3). In contrast, the flight route doses calculated for GLE 69 were much worse, did not show any significant peak, and agreed only within ±90 % from the median (Figure 4).

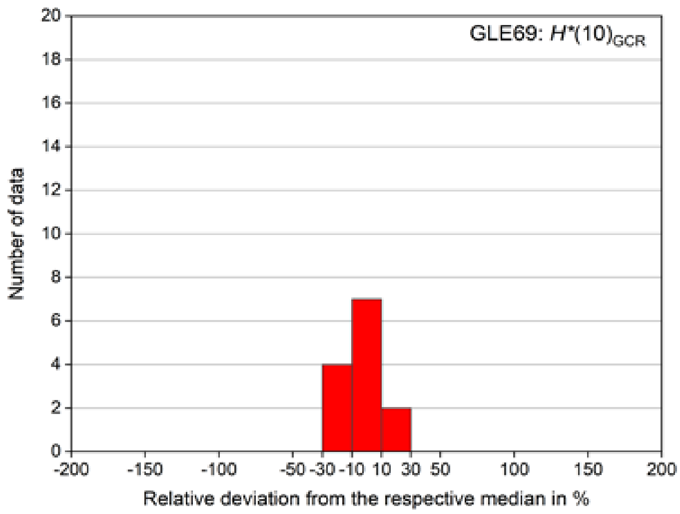

Figure 3. *Frequency distribution of relative deviation from the median of route effective doses calculated by nine computer codes, for three flights and January 2005; doses from the galactic component of cosmic radiation only (figure taken from Beck et al., 2021).*

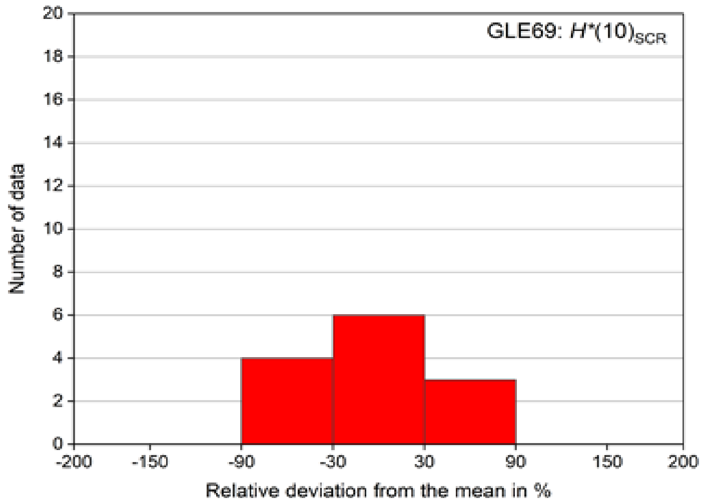

Figure 4. *Frequency distribution of relative deviation from the median of route effective doses, calculated by nine computer codes for three flights and January 2005; doses from ground level enhancement GLE 69 only (figure taken from Beck et al., 2021).*

The authors of the study concluded that "*one of the main reasons for the differences in the standard deviations from the respective medians of the results for GLE42 and GLE69 is the unequal identification and handling of the SCR characteristics by the different codes*". Therefore, they suggested to develop "*a traceable method to identify and handle the solar proton characteristics related to GLEs*". This was identified as a major scientific gap in radiation protection of aircrew. Furthermore, the authors saw "*an urgent need to validate codes used for dose assessment of radiation exposure due to solar particle events at aviation altitudes by experimental data*" (Beck et al., 2021).

3. Space Crew Dosimetry

3.1 Recent ICRP Activities

A few years after ICRP Publication 103 had been published (ICRP 2007), ICRP published a separate report dealing specifically with the assessment of radiation exposure of astronauts in space (ICRP 2013). Because the radiation field in space is very complicated and includes a vast variety of particles from photons, electrons, positrons, protons, neutrons up to heavy ions, all characterized by a vast range of energies, special emphasis was placed in this report on quality factors (Qs) expressed in terms of linear-energy-transfer (LET) or energy and particle charge, in an effort to take proper account of the different biological effects of these radiation qualities. It was emphasized that "*not all concepts of quantities defined for radiological protection applications on Earth are appropriate for applications in space missions, especially when risk assessment is an important task*" (ICRP 2013). For example, a radiation weighting factor w_R of 20 for heavy ions regardless of their energy as recommended in ICRP Publication 103 (ICRP 2007) for radiological protection on Earth, was not considered appropriate and the use of Q was recommended instead.

In 2018, the International Systems Maturation TEAM (ISMT-Radiation), which includes representatives of all space agencies involved in the operation of the International Space Station (ISS), requested ICRP to assess the role of radiation effects to the central nervous system, of cardiovascular disease, of the occurrence and latency of lens opacification, during space flight, and to provide recommendations on a common risk assessment framework and on exposure limits for cancer risks. Analyses should be informed by the choice of suitable example missions. This request prompted ICRP to establish Task Group 115 "Risk and Dose Assessment for Radiological Protection of Astronauts" which kicked-off at the ICRP Symposium 2019 in Adelaide, Australia.

The work programme of TG115 includes describing the methods used for dose and risk assessment by space agencies involved in ISS (Canadian Space Agency, European Space Agency, Japanese Aerospace Exploration Agency, National Aeronautics and Space Administration, Russian Space Agency). Two example missions were defined, a cislunar mission and a lunar surface mission. For these missions, radiation exposures and radiation risks from galactic cosmic radiation and from a solar particle event will be assessed and compared. The Task Group is currently reviewing the scientific evidence on radiation-related tissue reactions (anything new since ICRP Publication 118 (ICRP 2012)) and on relevant stochastic effects including cancer. Further emphasis is to examine various available risk metrics that can be used to assess radiation-related health risks and communicate those to astronauts. On a long term, this TG or a follow-up TG may develop a comprehensive framework for risk and dose assessment for radiological protection of astronauts, which might also be of relevance for space tourism (Rühm et al., 2021).

3.2 Recent NASA Activities

Most of NASA's activities to date have focused on low Earth orbit (LEO) regions which correspond to altitudes of less than 2,000 km (less than about one-third of the radius of the Earth). Exceptions were the Moon missions of the Apollo programme which were beyond LEO. In all those missions, be it LEO or beyond LEO, astronauts have to deal with hazards and risks from various sources including those from ionising radiation. As for radiation-related cancer risk, the current NASA standard says that "*Planned career exposure to ionizing radiation shall not exceed 3 percent risk of exposure-induced death (REID) for cancer mortality at a 95 percent confidence level to limit the cumulative effective dose (in units of Sievert) received by an astronaut throughout his or her career*" (NASA 2014) where the 95 % percent confidence level refers to the 97.5 percentile of the REID uncertainty distribution. A REID of 3 % means that three out of 100 astronauts would die from cancer due to the radiation they had received during their space missions, at some time during their life. It is worth noting that, because radiation-induced risks are sex-dependent, this standard implies that maximum permissible mission durations may be different for male and female astronauts. Let us assume, as an example, that a male and female astronaut, both at age 44 y, had participated in a space mission with a duration of 320 d. Then, for a second mission at age 47 y, the remaining permissible mission duration would be 211 d for the male astronaut, but only 43 d for the female astronaut (example taken from NASEM (2021)).

Recently, NASA has initiated a process to revisit this standard, because there are current plans for longer-term missions including missions to the Moon and to Mars. Furthermore, new scientific evidence in radiobiology and radio-epidemiology may require an update of the previously used cancer risk model and the included assumptions on sex differences in radiation-related cancer risks. In particular, NASA considers to base a new standard on the mean 3 % REID of a 35 y old female (instead of the 97.5 percentile of the REID calculated for an individual astronaut), which would translate to a single effective-dose career limit of about 600 mSv, to be equally communicated to male and female astronauts. For comparison, the current NASA approach results in space permissible exposure limits (SPELs) of about 180 mSv for female astronauts and of about 700 mSv for male astronauts (NASEM 2021).

On request of NASA, the US National Academies of Sciences, Engineering, and Medicine (NASEM) has established a Committee on "Assessment of Strategies for Managing Cancer Risk Associated with Radiation Exposure During Crewed Space Missions", to review and assess NASA's risk assessment and management for long-term space missions with respect to radiation-related cancer. Overall, this Committee recommended NASA to proceed with the proposed approach (NASEM 2021). They added, however, that "*in the near future, NASA should re-examine whether to use risk of exposure-induced death (REID) or other metrics, or a combination of metrics, in setting the dose-based space radiation health standard*". In this context, it is worth noting that long-duration missions as those to Mars will likely lead to radiation exposures that may well be above the proposed new standard of 600 mSv effective dose. This demonstrates the need for implementation of a waiver to the radiation health standard, which in turn highlights the need for a proper communication of the proposed approaches. While NASA has suggested traffic-light colour bands using estimated effective mission doses and the SPEL for categorisation and communication of space radiation risks, the NASEM Committee has recommended that "*NASA should provide all astronauts with an individual radiation risk assessment and revise the risk communication system (i.e., the traffic light) for the updated space radiation standard*" (NASEM 2021). This should also include communication of a more detailed and comprehensive picture of an astronaut's radiation-related cancer risk. As for exposures above the proposed standard of 600 mSv, the Committee recommended that NASA "*should develop a protocol for waiver of the proposed space radiation standard that is judicious, transparent, and informed by ethics*". In general, NASA was advised to develop a research agenda for radiation risk communication.

The Committee acknowledged that the focus of a single dose limit would provide equality of opportunity for both male and female astronauts without reference to age. On ethical grounds, choice of a 35 y females, i.e., of the most vulnerable among possible astronauts, for calculating the REID is considered the most protective approach. However, use of the 3% mean REID instead of the 97.5% quartile of the REID distribution would allow astronauts, for example on a Mars mission, to be exposed to higher radiation doses than currently allowed, and potentially even higher than the proposed new standard of 600 mSv. The resulting higher radiation-related cancer risk "*seems to conflict with an ethics commitment to protection from harm, minimization of risk, and NASA's requirement to ensure astronaut safety by keeping exposures as low as reasonably achievable*".

The Committee concluded that NASA should "*offer explicit ethics justifications for the approach adopted and the resulting standard, to be shared with astronauts and their families, as well as made publicly accessible*" (NASEM 2021).

4. References

Beck, P., Bottollier-Depois, J.F., Bütikofer, R., Flückiger, E., Fuller, N., Klein, K.-L., Latocha, M., Mares, V., Matthiä, D., Rühm, W., Comparison of Codes Assessing Radiation Exposure at Aviation Altitudes in Case of Solar Particle Events EURADOS Report 2021-03, ISSN 2226-8057, ISBN 978-3-943701-27-2 (2021), DOI: 10.12768/zmq7-bv59.

Bottollier-Depois, J.F., Beck, P., Latocha, M., Mares, V., Matthiä, D., Rühm, W., Wissmann, F., Comparison of Codes Assessing Radiation Exposure of Aircraft Crew due to Galactic Cosmic Radiation. European Commission. Radiation Protection 173, 1-61, ISSN 1681-6803 (2012a).

Bottollier-Depois, J.F., Beck, P., Latocha, M., Mares, V., Matthiä, D., Rühm W., Wissmann, F., Comparison of Codes Assessing Radiation Exposure of Aircraft Crew due to Galactic Cosmic Radiation. EURADOS Report 2012-03, ISSN 2226-8057, ISBN 978-3-943701-02-9 (2012).

European Union, Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation, Official Journal of the European Communities, L159, 29 June 1996 (1996).

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Environmental Radioactivity and Radiation Exposure – Annual Report 2018 (2019).

International Commission on Radiological Protection, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Ann. ICRP, 21(1-3) (1991).

International Commission on Radiological Protection, 2012 ICRP Statement on Tissue Reactions / Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context. ICRP Publication 118. Ann. ICRP 41(1/2) (2012).

International Commission on Radiological Protection, Assessment of Radiation Exposure of Astronauts in Space. ICRP Publication 123. Ann. ICRP 42(4) (2013).

International Commission on Radiological Protection, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Ann. ICRP, 37(2-4) (2007).

Lindborg, L., Bartlett, D., Beck, P., McAulay, I., Schnuer, K., Schraube, G. and Spurny, F., EURADOS. Cosmic Radiation Exposure of Aircraft Crew: Compilation of Measured and Calculated Data. European Commission. Radiation Protection 140. 1-271, ISBN 92-894-8448-9 (2004a).

Lindborg, L., Bartlett, D., Beck, P., McAulay, I., Schnuer, K., Schraube, H., and Spurny, F., Cosmic radiation exposure of aircraft crew: compilation of measured and calculated data, doi.org/10.1093/rpd/nch232, Radiat Prot Dosim. 110(1-4), 417-422 (2004b).

Mares, V., Maczka, T., Leuthold, G., and Rühm, W., Air crew dosimetry with a new version of EPCARD, Radiat. Prot. Dosim. 136(4), 262-266 (2009).

NASA, NASA spaceflight human system standard. Vol. 1, Revision A: Crew health. NASA-STD-3001 (2014).

NASEM, Space Radiation and Astronaut Health: Managing and Communicating Cancer Risks. National Academies of Sciences, Engineering, and Medicine. Washington (2021), DC: The National Academies Press. https://doi.org/10.17226/26155.

Rühm, W., Li, C., Reitz. G., Activities of ICRP towards assessment of radiation exposures and related risks of astronauts. StrahlenschutzPraxis 4/2021, 52-54, ISSN 0947-434X (2021).

Schraube, H., Leuthold, G., Heinrich, W., Roesler, S., Mares, V. and Schraube, G.: EPCARD – European program package for the calculation of aviation route doses, User's manual. GSF-National Research Center, Neuherberg, Germany (2002). ISSN 0721 - 1694. GSF-Report 08/02.

StrlSchV (2001) German Radiation Protection Ordinance „Verordnung über den Schutz vor Schäden durch ionisierende Strahlen, 20. Juli 2001, Bundesgesetzblatt Teil I Nr. 38, 1714-1846 (in German).

Dosimetry in pulsed fields and mixed fields (including radiation protection of personnel in proton therapy facilities)

Marco Caresana[3]

Department of Energy – Politecnico di Milano – Via Lambruschini, 4 20156 Milano Italy

Abstract

Dosimetry in pulsed and mixed radiation fields is an important issue in radiation measurements. Despite pulsed fields are a characteristic of several workplace radiation fields, at present there are few instruments conceived for this kind of radiation and most important, no reference facility for instruments calibration. This issue is also mentioned in the EURADOS Strategic Research Agenda (SRA) (Harrison et al., 2021) that stresses the need of developing new detectors and associated electronics. Well established accelerator technologies, like for instance medical LINACs for cancer treatment, accelerate bunches of particles in a short time, typically in the range of µs, spaced by a relative long time of beam off. Emerging acceleration technologies, like laser-driven accelerators or free electron laser, reduce the pulse duration down to fs with extremely low repetition rate. Also, future technologies like fusion facilities are expected to produce pulsed radiation field. Recently, acceleration of primary particles in short and very intense pulses is attracting interest because of the promising flash radiotherapy. (Schüller et al., 2020) The flash effect consists in treating the cancer with extremely high doserate (above about 1 MGy/s), obtaining the same effect on the tumor, but sparing the surrounding healthy tissue. Within the EURADOS WG11 "High energy radiation fields" several actions have been taken to study pulsed fields and other specific tasks are running. Other actions have been organized in collaboration with the EURADOS WG9 "Radiation dosimetry in radiotherapy", when medical applications are concerned. The main aim of these actions is to intercompare commercial instruments or prototypes, under different experimental conditions and identify the possible issues in relation to the specific environment. The paper describes some of the WG11 experiences.

1. Introduction

In radiation dosimetry, it is quite common to face the problem of measuring in pulsed and mixed fields. The typical challenge characterizing mixed fields, that is the discrimination between the neutron and photon components, is further complicated by the pulsed time structure of radiation fields. An example are medical LINACs, where the electrons beam is accelerated in bunches whose duration is in the range of few µs and the repetition rate starches from tens of Hz up to 1 kHz (Isidori et al., 2021). If the electrons acceleration

[3] Corresponding author: Marco Caresana Department of Energy – Politecnico di Milano – Via Lambruschini, 4 20156 Milano Italy, marco.caresana@polimi.it

potential exceeds 6 MV the neutron contamination of the therapeutic photon beam becomes important and cannot be neglected for the justification of the practice.

In addition to the well-established technology of medical LINACs, several emerging technologies, not only in the medical field, are characterized by pulsed radiation fields. The laser driven acceleration technology (Badziak, 2018) permits to obtain bursts of radiation with duration in the range of fs. Pulses of similar characteristic are also obtained in free electron laser. (Strabel et al., 2017)

Stray radiation produced around the above-mentioned machines, maintains the same time structure as the primary beam. This limits the availability of instrumentation, as active instruments operating in pulse mode are affected by important dead time losses during the burst and the classical procedure for dead time compensation (Knoll, 2010), valid for steady fields, cannot be applied.

As far as the dosimetry of the primary beam is concerned, and in case of ultra-high dose pulses, in the range of MGy/s, also instruments operated in current mode, like ion chamber, can fail because of ion recombination losses. This is the case of flash radiotherapy where the beam delivery monitoring must rely on instruments other than ion chamber. This is still an open field of research. Figure 1, taken from (Schüller et al., 2020), shows schematically the current situation. The red line indicates the limit of operation of ion chamber.

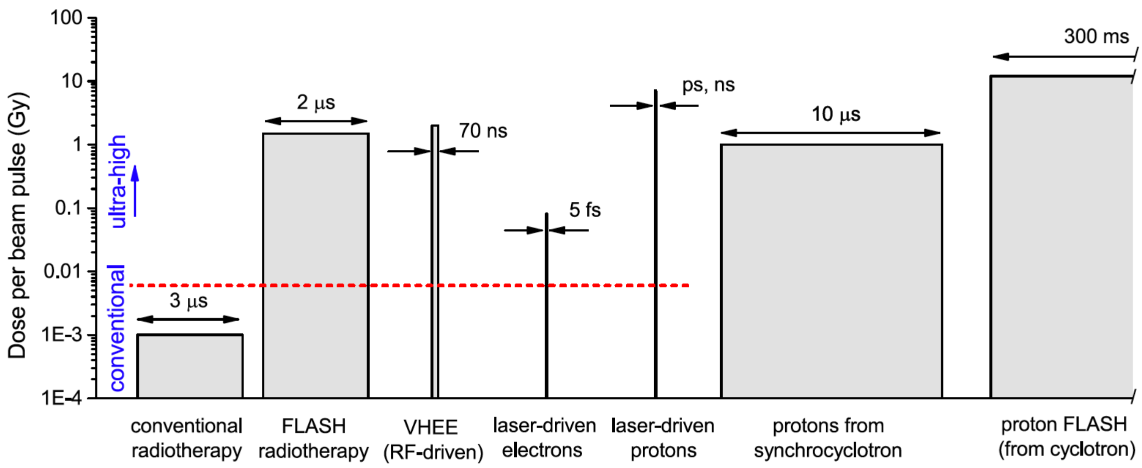

Figure 1. *Limit of operation of ion chamber (red line) compared with the characteristics of different acceleration technologies candidate to obtain the flash effect for cancer treatment.*

2. Definition of pulsed fields

In this paper, the nomenclature could be sometime confusing as the word pulse can refer both to the radiation pulse and to the electronic pulse in output from a detector operated in pulse mode. In the parts of the paper, where the nomenclature can lead to misunderstanding, when dealing with radiation pulse we will use the word "radiation burst" while the word "pulse" will be reserved for the detector output. As shown in figure 1, the burst duration depends strongly on the specific acceleration technology and spans over several order of magnitudes, from few fs to hundreds of ms. However, the definition of radiation burst cannot be independent of the instrument used. Let us consider detectors operated in pulsed mode; the pulse time resolution depends on the specific instrument and is typically in the range of few µs. Thus, radiation can be considered delivered in bursts (or, neglecting the disclaimer at the beginning of the paragraph, we can speak of pulsed fields) if the burst duration is lower or equal to the pulse duration. For detectors operating in current mode the detector resolving time is defined by the integration time of the ammeter (Knoll, 2010) that is generally in the range of tens/hundreds ms. So, the definition of radiation burst extends to longer duration.

The description above applies very well to photon detectors. In case of neutron detectors, the situation is quite different and somehow easier to handle.

The most widespread instrument for environmental neutron monitoring is the REM-counter. This instrument is based on a detector of thermal neutrons surrounded by a neutron moderator made of material with high hydrogen content. The main feature of the REM-counter is that the response function R(E) is parallel to the fluence to $H^*(10)$ conversion coefficients $h^*(10)$. This characteristic is mathematically expressed by equation 1

$$K = \frac{h^*(E)}{R(E)} \tag{1}$$

Where *K* is a constant independent of, or smoothly dependent on energy. By applying the definition of $H^*(10)$ (see equation 2)

$$H^*(10) = \int h^*(E) \cdot \phi(E) dE = \int K \cdot R(E) \cdot \phi(E) dE = K \int R(E) \cdot \phi(E) dE = KL \tag{2}$$

it can be demonstrated the constant K multiplied by the instrument reading L (expressed in counts) returns the value of $H^*(10)$.

In case the REM-counter is irradiated by a very short neutron burst of duration *T,* neutrons take some time to slow down their velocity until they become thermal. Reached this stage they drift until they find their way to the inner detector. This transient is called Thermalization and Drift Time (TDT). The effect of the TDT is to spread out the time of arrival of thermal neutron to the inner detector. The value of the TDT has been evaluated with Monte Carlo (MC) simulation (using the MC neutron photon transport code MCNP 6.2) irradiating moderation spheres with monoenergetic neutrons of 1 MeV and 10 MeV and scoring the variation in time of the reaction rate in the thermal neutron detector composed of a sphere of 15 cc filled with ^{3}He. Figure 2 illustrates the effect of the TDT on spheres of different diameter irradiated with neutrons of different energies. The time of arrival of thermal neutron can be very well approximated by a decreasing exponential (see equation 3 where R is the reaction rate) with a characteristic decay time τ depending on the neutron energy and sphere dimension. τ is around 100 µs, increasing with decreasing neutron energy and for a fixed energy increases with the sphere diameter.

$$R(t) = R_0 \cdot e^{-t/\tau} \tag{3}$$

If the burst duration is lower than τ the definition of "pulsed field" is fulfilled. However, it does not matter if the original burst duration is in the range of fs up to µs. As far as the REM-counter is concerned, the time distribution of the reaction rate is defined by equation (3). The effect of TDT mitigates the problem because it reduces the interaction rate in the inner detector, however, important dead time losses remain, also for radiation bursts of relatively low intensity.

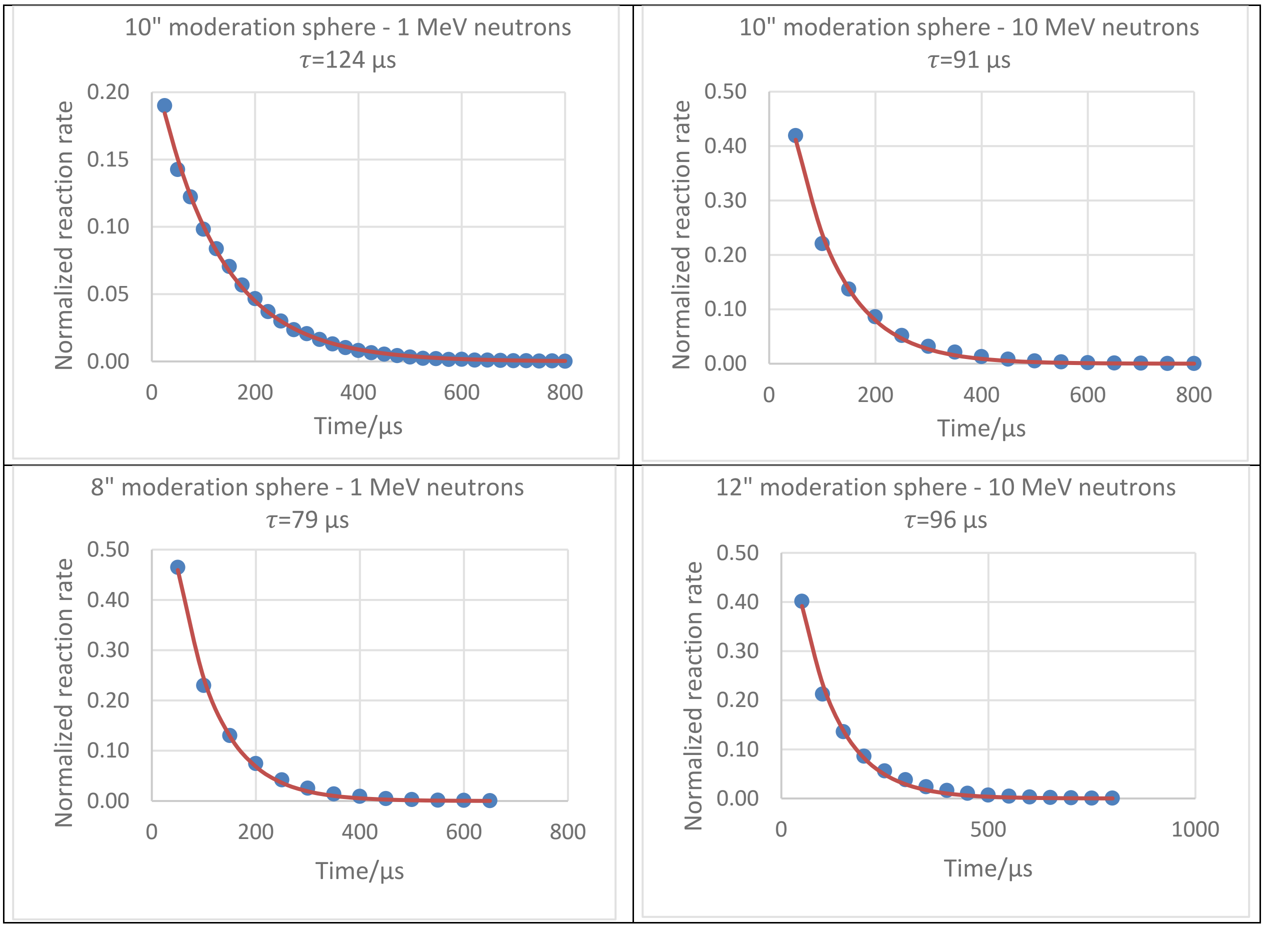

Figure 2. *Simulation with MCNP6.2 of the diffusion and drift time for different spheres and different neutron energies. The continuous line is the exponential fit of equation 3, and the corresponding characteristic time τ is reported in the graph titles.*

This can be seen with an example. Let us consider a REM-counter with sensitivity of 1 count per nSv and a typical pulse shaping time around 2-3 µs, that, for a semi-Gaussian shaping, results in a dead time in the range 10-15 µs (Knoll, 2010). Let us assume a burst intensity of 100 nSv, meaning 100 counts/burst. If τ =100 µs, equation (3) indicates that on average 37 counts occur in 100 µs, that means a reaction rate of 0.37 MHz. It is almost impossible to cope with such a high reaction rate, considering a dead time around 10 µs. In order to measure high intensity neutron radiation bursts some modification of the standard REM-counters is needed.

3. The LUPIN REM-counter

The original idea of modification of the working principle of a standard REM-counter has been proposed about 10 years ago (Ferrarini et al., 2010) followed by characterization and improvements (Caresana et al. 2013; Caresana et al., 2014a; Aza et al., 2014a; Aza et al., 2014b, Manessi, 2015).

The basic idea of the LUPIN (**L**ong interval, **U**ltra wide dynamic, **PI**le-up free **N**eutron survey meter) is to change the classical electronic chain, composed by preamplifier, shaper amplifier, discriminator and counter, with a scheme depicted in Figure 3.

The proportional counter can be either an ^3He of BF_3 proportional counter. The proportional counter output current enters in a logarithmic amplifier that outputs a voltage signal that is fed to an analogue to digital converter (ADC) via a driver capable to remote the digital unit up to 100 m. The analogue signal is sampled at 10 MHz and the digital signal is processed with a Field Programmable Gate Array (FPGA) that converts back the voltage signal into digital current. The current is digitally integrated over a time (at least 4-5 τ) to pick up the entire charge generated by the radiation burst. The total charge, divided by the charge expected by a single neutron interaction, gives the number of interacting neutrons, i.e. the counts.

As the LogAmp can accept input only positive and non-zero current, a bias current must be injected into the LogAmp. In addition, the proportional counter positive current is picked up from the cathode. This feature imposes the electrostatic shielding of the whole proportional counter to avoid noise pick up.

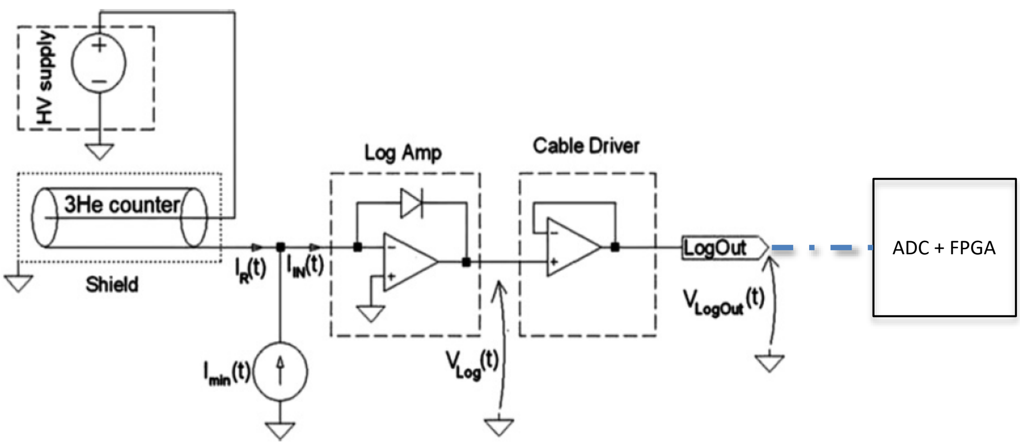

Figure 3. *Electronic acquisition chain of the LUPIN.*

This way of signal processing is called in “charge mode”, it is quite effective, except for the situation where an intense and steady photon field is superimposed to the neutron burst. Under this condition, the gamma field generates a background current that, once integrated, cannot be discriminated by the neutron induced charge.

To bypass this problem, the LUPIN implements a second procedure called derivative mode. In this operation mode the FPGA computes the derivative of the output current. As a neutron interaction produces a very step increase of the current, the derivative results in a very sharp peak. Figure 4 shows an example how the derivative in mA/s appears. The derivative is computed with equation (4).

$$\frac{d(I_n)}{\delta t} = \frac{1}{2\delta t} \cdot (I_{n+1} - I_{n-1}) \quad with \quad \delta t = 100\, ns \tag{4}$$

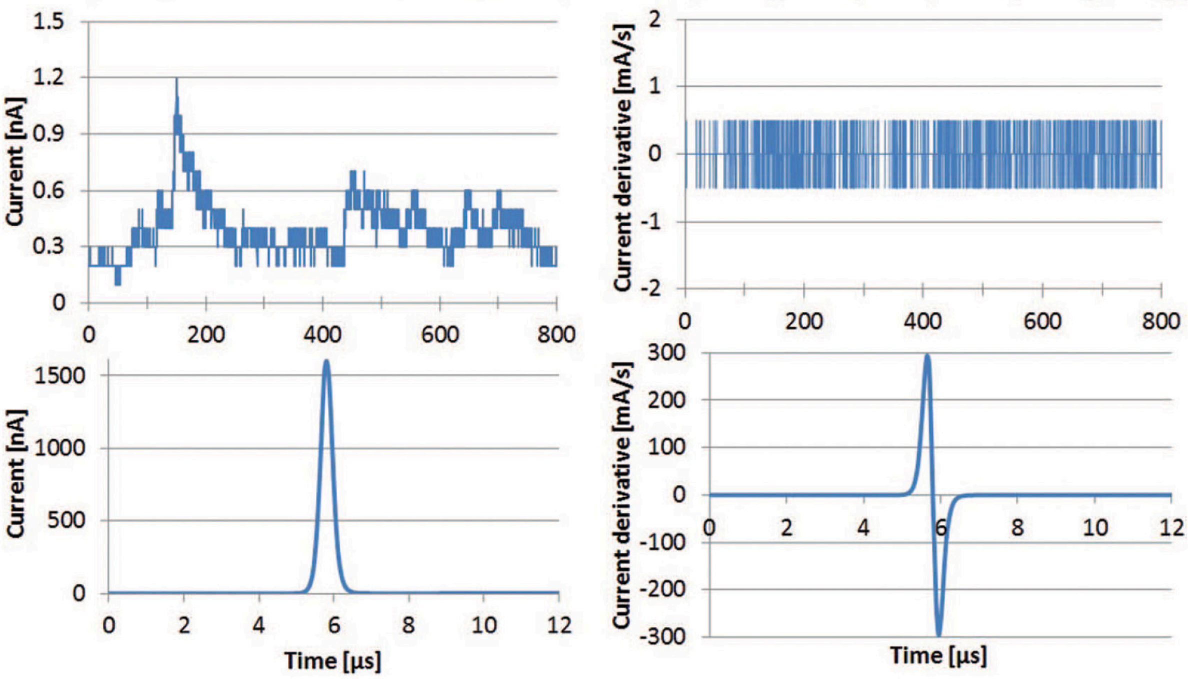

Figure 4. *Current signal (left) and derivative signal (right) generated by a photon field (top) and a neutron interaction (bottom).*

The derivative is computed over a time of 200 ns that can be considered an equivalent dead time. This is two orders of magnitude lower than the typical dead time of conventional REM-counters. The derivative time is, at present, limited by the sampling frequency, but in principle it can be further reduced increasing the sampling time.

The derivative mode has the advantage of improving the gamma rejection capability as the smoothly variable photon generated current is cut out by the derivative.

4. Experimental activity performed by the EURADOS WG11

The EURADOS WG11 "High energy radiation fields" includes, among its activities, a specific task devoted to pulsed radiation fields. An important intercomparison was organized in 2012 at the cyclotron of the Helmholtz-Zentrum Berlin für Materialien und Energie GmbH. The aim was to set up a temporary reference facility for pulsed neutron fields to intercompare the response of REM-counters, both commercial instruments and prototypes proposed by participant institutions.

A second intercomparison was recently organized in collaboration with the WG9 at the Maastro Pulsed Proton Therapy centre in the Netherlands, measuring the stray neutron filed around the synchrocyclotron Mevion S250i. The experimental run included both on beam and off beam measurements and the WG11 was in charge of coordinating the stray neutron field measurement with REM-counters.

4.1 Experiment at the Helmholtz-Zentrum Berlin (HZB)

This intercomparison exercise is fully described in (Caresana et al., 2014b). The HZB host a cyclotron accelerating protons up to 68 MeV. In is mainly used for medical applications, but a secondary irradiation room was available for research purposes.

Figure 5 shows the experimental room, the tungsten target used to produce neutrons and the neutron spectrum obtained in the measurement position 50 cm away from the target.

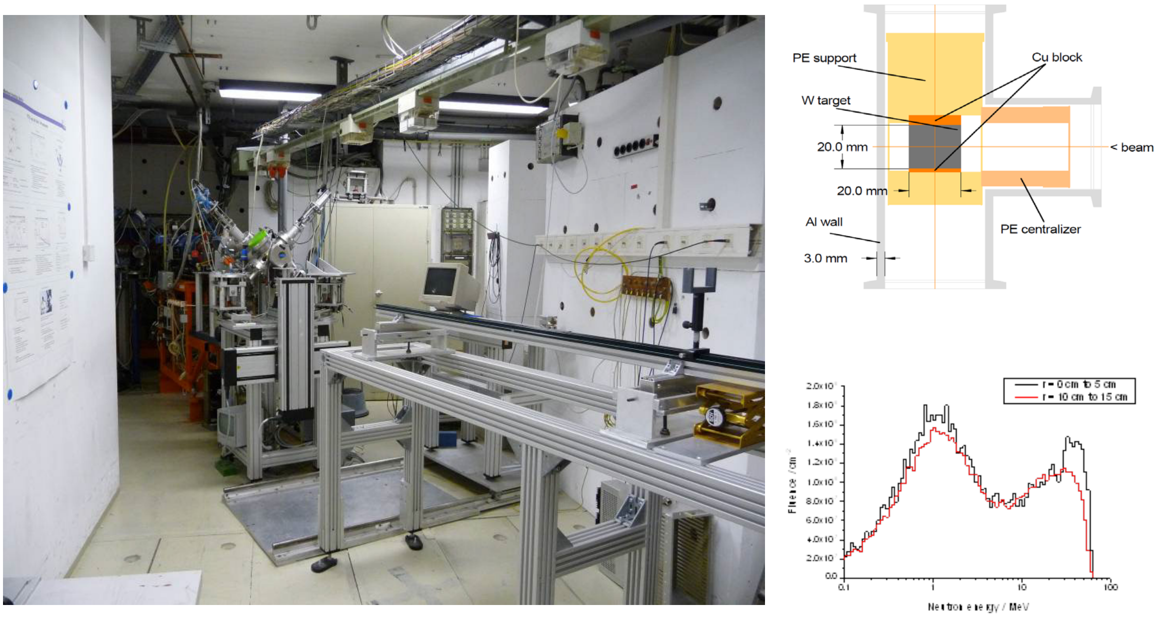

Figure 5. *Picture of the experimental hall (left) sketch of the W target (top-right) and MC simulation of the neutron spectrum at the measurement position (right-bottom).*

The proton beam was permanently directed to a beam dump and a kick magnet was used to bend the beam into the W target for a fixed time ranging from 1 μs to 40 μs. this time was used to define the burst duration and was always kept below 100 μs that is a typical value of τ. By changing the burst duration and the proton current it was possible to obtain neutron bursts of increasing intensity, used to test the instruments linearity. Table 1 shows the settings corresponding to the 15 different burst intensities. The results in terms of instrument linearity are shown in Figure 6 for the tested REM-counters.

On average, standard REM counters start losing linearity at doses per burst ranging from 1 nSv and 10 nSv. The only exception is the LUPIN, especially in the BF3 version, that maintains the linearity up to about 500 nSv. Of course, also the LUPIN starts losing linearity for more intense dose per burst. In fact, several, almost simultaneous interactions, generate a huge space charge around the anode wire that electrostatically shields it, causing a reduction of the multiplication factor. This effect explains also the reason why the LUPIN in the ^{3}He version reaches sooner the saturation. The reduction of the potential seen by the anode, depends on the charge density, according to the Poisson equation. As the ^{3}He proportional counter has an active volume (17 cc), much lower than the BF3 (100 cc), for a similar charge generated, the charge density in BF3 is lower than in ^{3}He.

However, the amount of charge generated by the burst is exactly the quantity measured by the LUPIN, so a compensation based on the solution of the Poisson equation has been proposed (Cassell et al., 2015).

Table 1: *List of accelerator settings to obtain the reference burst intensities (column in bold) used to evaluate the REM-counters linearity*

Setting n°	Ion current [pA]	Burst current [nA]	Burst length [µs]	Burst charge Q_i [fC]	Reference burst yield [nSv per burst]	Average dose rate [µSv·h^{-1}]	Burst dose rate [Sv·h^{-1}]
1	0.5	5	1	5	**0.077**	27.72	0.28
2	1.5	15	1	15	**0.231**	83.16	0.83
3	3	30	1	30	**0.462**	166.32	1.66
4	5	50	1	50	**0.770**	277.2	2.77
5	10	100	1	100	**1.540**	554.4	5.54
6	25	250	1	250	**3.850**	1386	13.86
7	50	500	1	500	**7.700**	2772	27.72
8	75	750	1	750	**11.550**	4158	41.58
9	100	1000	1	1000	**15.400**	5544	55.44
10	250	250	10	2500	**38.500**	13860	13.86
11	500	500	10	5000	**77.000**	27720	27.72
12	1000	1000	10	10000	**154.000**	55440	55.44
13	3000	800	40	32000	**492.800**	177408	44.35

Concerning the standard REM-counters, the experimental deviation from the ideal linearity, permitted to identify a specific value of the reference dose per burst that causes the instrument to underestimate by a factor 2. The value is called D_{half}.

Table 2 reports for each REM counter the specific value of D_{half}. The experimental knowledge of D_{half} permits to introduce a compensation formula (equation 5)

$$D_{meas} = \frac{D_{ref}}{1+\left(D_{ref}/D_{half}\right)} \tag{5}$$

Where D_{meas} is the dose per burst measured by the specific REM-counter and D_{ref} is the reference dose per burst.

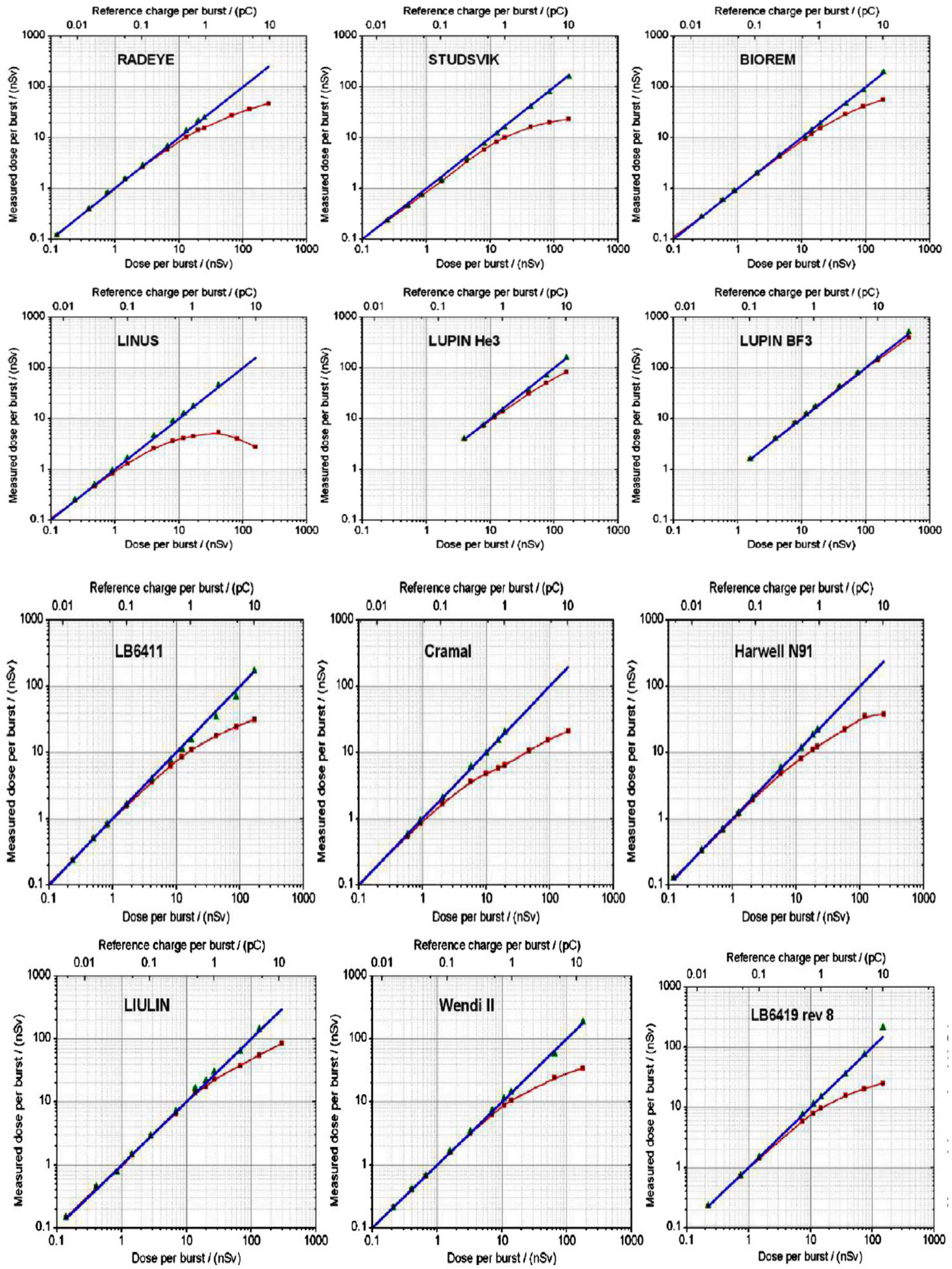

Figure 6. *Instruments linearity. Almost all the REM -counters start loosing linearity from a dose per burst in between 1 nSv and 10 nSv. The only relevant exception is the LUPIN BF3 that exhibits a good linearity up to 500 nSv.*

Equation 5 permits to foresee the instrument response for a specific value of D_{ref}. Of course, equation 5 can be inverted to assess the corrected dose per burst (reference dose) starting from D_{meas}.

The knowledge of D_{half} can in principle solve the compensation problem in case D_{meas}, for each single burst, is known. Unfortunately, this quantity is not easy to retrieve because the REM-counter outputs the dose-rate or the dose integrated over a user selectable time. In general, the number of bursts occurring in the integration time is unknown and, in addition, each burst can have a different D_{meas}. Thus, the practical applicability of equation 5 is limited to very specific situation, for instance if the machine logfiles are known.

The value of D_{half} is a good indication of the capability of the specific REM-counter to cope with pulsed fields. The higher is D_{half} and better the instrument performs in pulsed field. A REM counter can be considered linear until a burst intensity about $\frac{1}{4} \cdot D_{half}$ (expected 20 % underestimation).

Table 2: *Values of D_{half} measured for the tested REM-counters (from Caresana et al., 2014b)*

Instrument	Half response burst dose D_{half} [nSv]
LUPIN BF_3	1808
LUPIN ^3He	182
LB 6419	28
WENDI II	42
BIOREM	79
LB 6411	38
Studsvik 2202D	27
RadEye	25
Harwell N91	19
Linus	6
Cramal31	8
LIULIN	53

4.2 Experiment at Maastro Pulsed Proton Therapy centre

The experiment described in 4.1 was mainly aiming at characterizing the instrumentation. The experiment described in this section is more focused on using reliable instrumentation to characterize the radiation field. Further detail on this experiment are in Zorloni et al., 2022.

The Maastro proton therapy center hosts a synchrocyclotron Mevion S250i, which represents the state-of-the-art in proton therapy. The proton beam is delivered in pulses 10 μs in duration at a maximum repetition rate of 750 Hz Max. The doserate is tuned by changing the repetition rate. The max proton energy is 227 MeV and can be reduced down to 13.5 MeV with a passive energy degrader.

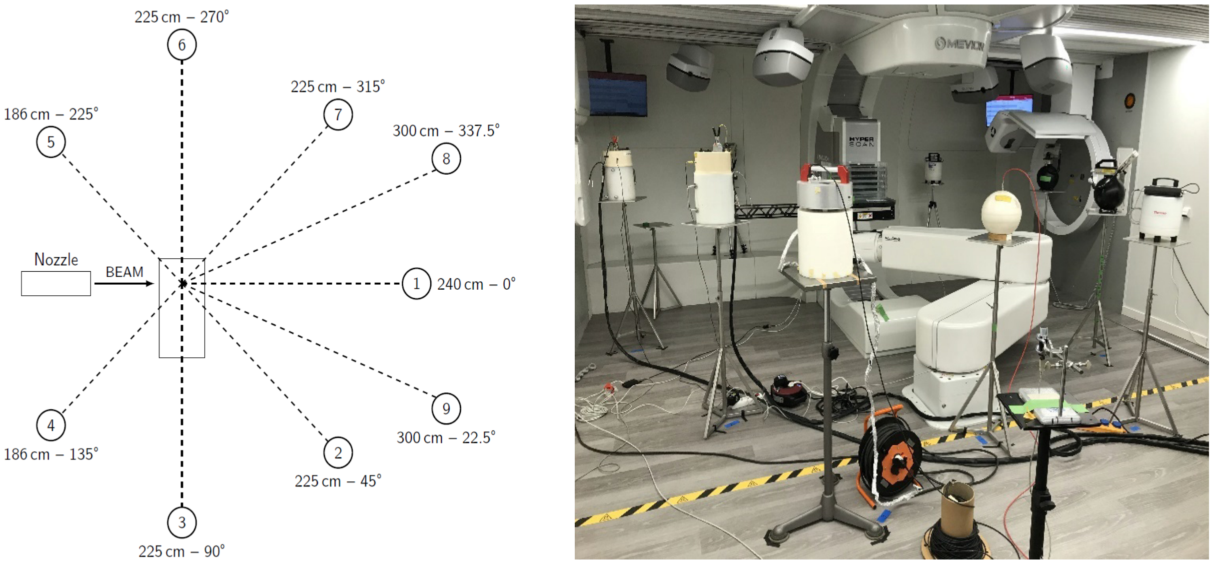

Figure 7. *Schematic of the measuring positions (left) and picture of the experimental hall with REM-counters in place.*

The intercomparison involved 9 REM-counters, some of which already characterized in the HZM experiment, including the LUPIN that is considered as a reference REM-counter, considering the superior performance demonstrated. The measurement positions are described in Figure 7, the whole irradiation campaign was composed of 9 runs to let each detector rotate and measure in each position. A water tank phantom (30 cm x 30 cm x 60 cm) was employed to simulate a patient treatment protocol.

Figure 8 (left) summarized the experimental result comparing the measurements of the 9 REM-counters in each position. Neutron dose shown on the y axis, is normalized to the dose in the water tank. The LUPIN measures a higher neutron dose in all positions, indicating that the neutron burst intensity causes saturation of the standard REM counters. Figure 8 (right) presents the same dataset reporting in the x axis the normalized neutron dose measured by the LUPIN and in the y axis the measurement of each detector divided by the dose measured by the LUPIN. The two WENDI-II REM counters clearly show higher underestimation with increasing dose. In addition, these two instruments seem to perform better that the other standard REM-counters, in agreement with their higher D_{half}.

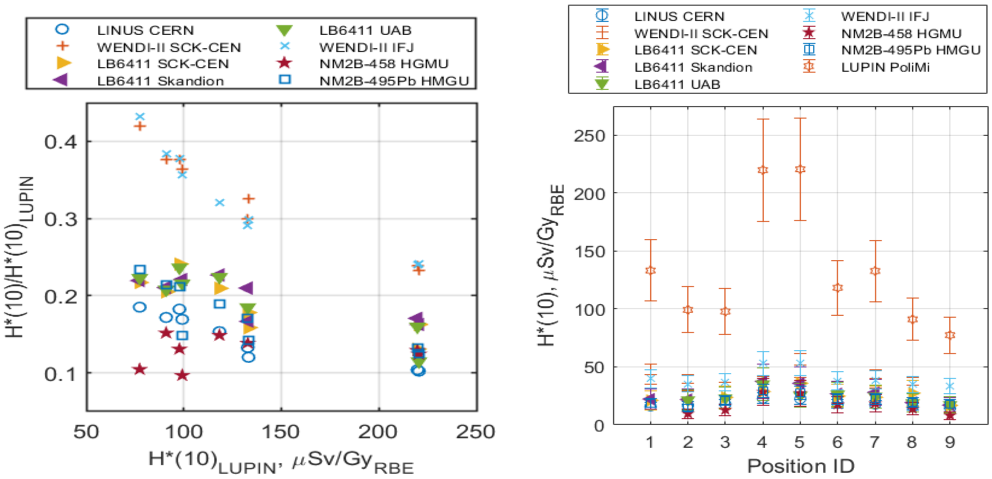

Figure 8. *Comparison of the instruments response in each measurement position (left) and measurement underestimation of each REM counter compared to the LUPIN, as a function of the dose.*

A qualitative analysis of Figure 8 indicates an agreement with the findings reported in 4.1. To make the comparison more quantitative, the approach was to check if equation 5 can effectively foresee the experimental underestimation, assuming the dose per burst measured by the LUPIN as D_{ref}. The check went through the following steps

1) Take the dose profile in time measured by the LUPIN (resolution 1s) for each run. An example is reported in Figure 9.

2) Derive from the machine logfile the number of pulses in each second

3) Calculate the average dose per pulse in each second (D_{ref})

4) Use D_{ref} to calculate the expected D_{meas} according to equation (5)

5) Correct the D_{meas} for the difference of the neutron spectrum in the present experiment and the one described in 4.1

6) Compare the experimental ratio between the standard REM-counter reading and the LUPIN one (R_{exp}) with the expected ratio (R_{theo}) calculated in the steps 1) to 5).

The comparison in point 6) is shown in Figure 10, one graph for each REM-counter. The x axis reports R_{exp} and the y axis R_{theo}.

If points lay on the bisector, it means that equation (5) foresees correctly the standard REM-counters underestimation and that D_{ref} is correctly measured, i.e. measurements with the LUPIN are not importantly affected by saturation.

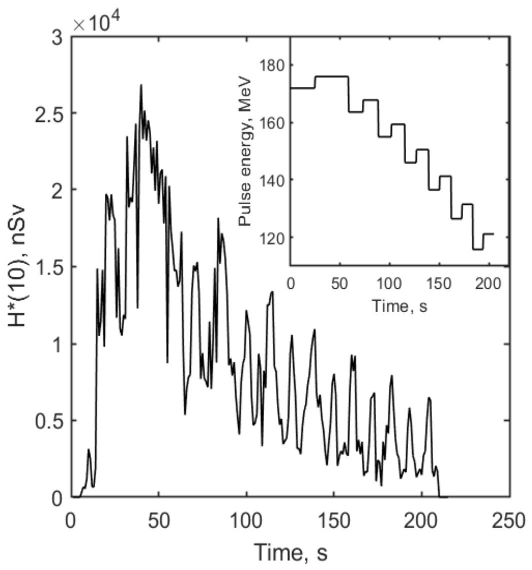

Figure 9. *Example of a dose profile measured by the LUPIN with 1 s time resolution. The graph inset shows the time profile of the proton energy.*

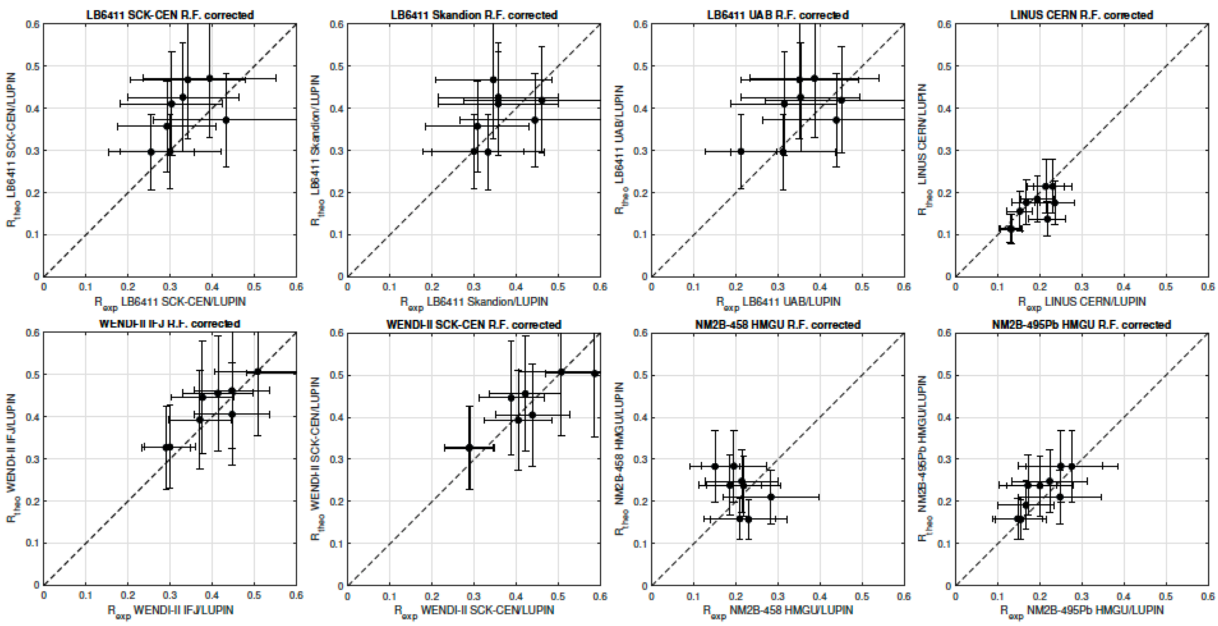

Figure 10. *Comparison between the experimental (R_{exp}) and expected (R_{theo}) underestimation of a standard REM-counter, assuming the LUPIN as reference instrument. If the experimental points are on the axis bisector, there is agreement between experimental and expected underestimation. The uncertainty bars include the calibration uncertainty of the REM-counters, the uncertainty of the response functions and the uncertainty on the simulated neutron spectrum.*

5. Conclusions

The following final remarks can be drawn:

- Pulsed radiation fields represent a common exposure situation, nevertheless, only a small number of detectors have been conceived for measuring under these conditions.
- In case of pulsed neutron fields, the effect of the thermalization and drift time mitigates the problem, nevertheless, standard REM-counters show limited linearity, with an upper ceiling around 5-10 nSv/burst.
- Compensation algorithms can be used, basing on the compensation of every single burst. However, this can be done only in specific situations.
- The LUPIN, characterized in reference pulsed fields, has proved to be coherent in workplace fields and represents a solid alternative to the standard REM-counters. In fact, the LUPIN maintains the same performance as any other REM-counters when working in non-pulsed radiation fields, but extend the linearity up to about 500 nSv/burst.

Unfortunately, a metrological grade reference facility for instrument calibration in pulsed neutron field does not exist. The experiment carried out by the WG11, as described in paragraph 4.1, was based on the temporary characterization of the experimental facility, that was dismantled immediately after the experimental run.

At present, investigators and even manufacturers have no possibility to experimentally verify their instruments or prototypes.

This is an important metrological gap that must be filled to provide metrological traceability for measurements in pulsed neutron fields.

6. References

Aza, E., Caresana, M., Cassell, C., Charitonidis, N., Harrouch, E., Manessi, G. P., ... & Silari, M. (2014a). *Instrument intercomparison in the pulsed neutron fields at the CERN HiRadMat facility.* Radiation measurements, 61, 25-32.

Aza, E., Caresana, M., Cassell, C., Colombo, V., Damjanovic, S., Gilardoni, S., ... & Silari, M. (2014b). *Comparison of the performance of different instruments in the stray neutron field around the CERN Proton Synchrotron*. Radiation protection dosimetry, 161(1-4), 190-195.

Badziak, J. (2018). *Laser-driven ion acceleration: methods, challenges and prospects.* In Journal of Physics: Conference Series (Vol. 959, No. 1, p. 012001). IOP Publishing.

Caresana, M., Cassell, C., Ferrarini, M., Hohmann, E., Manessi, G. P., Mayer, S., ... & Varoli, V. (2014a*). A new version of the LUPIN detector: Improvements and latest experimental verification*. Review of Scientific Instruments, 85(6), 065102.

Caresana, M., Denker, A., Esposito, A., Ferrarini, M., Golnik, N., Hohmann, E., ... & Wielunski, M. (2014b). *Intercomparison of radiation protection instrumentation in a pulsed neutron field.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 737, 203-213.

Caresana, M., Ferrarini, M., Manessi, G. P., Silari, M., & Varoli, V. (2013). *LUPIN, a new instrument for pulsed neutron fields.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 712, 15-26.

Cassell, C., Ferrarini, M., Rosenfeld, A., & Caresana, M. (2015). *A novel technique for compensation of space charge effects in the LUPIN-II detector.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 804, 113-117.

Ferrarini, M., Varoli, V., Favalli, A., Caresana, M., & Pedersen, B. (2010*). A wide dynamic range BF3 neutron monitor with front-end electronics based on a logarithmic amplifier*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 613(2), 272-276.

Harrison, R. M., Ainsbury, E., Alves, J., Bottollier-Depois, J. F., Breustedt, B., Caresana, M., ... & Woda, C. (2021). *Eurados Strategic Research Agenda 2020: Vision for the Dosimetry of Ionising Radiation*. Radiation Protection Dosimetry, 194(1), 42-56.

Isidori, T., McCavana, P., McClean, B., McNulty, R., Minafra, N., Raab, N., ... & Royon, C. (2021). *Performance of a low gain avalanche detector in a medical linac and characterisation of the beam profile*. Physics in Medicine & Biology.

Knoll G. F., *Radiation Detection and Measurement*, 4th edition, John Wiley & Sons Inc, 2010.

Manessi, G. P. (2015). *Development of advanced radiation monitors for pulsed neutron fields* (Doctoral dissertation, University of Liverpool).

Schüller, A., Heinrich, S., Fouillade, C., Subiel, A., De Marzi, L., Romano, F., ... & Vozenin, M. C. (2020). *The European Joint Research Project UHDpulse–Metrology for advanced radiotherapy using particle beams with ultra-high pulse dose rates.* Physica Medica, 80, 134-150.

Strabel, C., Fuchs, A., Galev, R., Hohmann, E., Lüscher, R., Musto, E., & Mayer, S. (2017). *The future SwissFEL facility–challenges from a radiation protection point of view.* In *EPJ Web of Conferences* (Vol. 153, p. 07026). EDP Sciences.

Zorloni, G. et al., *Joint EURADOS WG9-WG11 rem-counter intercomparison in a Mevion S250i proton therapy facility with Hyperscan pulsed synchrocyclotron,* (2022) submitted to Physics in Medicine and Biology.

Computational dosimetry and use of artificial intelligence (AI)

Hans Rabus[4]

Physikalisch-Technische Bundesanstalt, Abbestrasse 2-12, 10587 Berlin, Germany

Abstract

Computational methods play an important role in radiation dosimetry. In the current (and emerging) system of radiological protection, the operation and protection quantities are defined via anthropomorphic computational phantoms and can only be determined by computational simulations. Similarly, computational dosimetry is essential for patient-specific dosimetry in many fields of radiation medicine in the frame of the move towards personalized medicine. New approaches such as flexible numerical phantoms and/or real-time dose assessment involve an increasing complexity of computational dosimetry. Methodologies based on artificial intelligence may offer a way to overcome the computational challenges associated with these developments.

This report briefly reviews the state of the art of the most commonly used computational dosimetry techniques, focusing on Monte Carlo techniques, followed by a cursory introduction to artificial intelligence and the potential of machine learning to accelerate computations in dosimetry. Finally, the challenges and caveats of established and emerging techniques of computational dosimetry are highlighted, and conclusions are drawn on the need for actions.

1. Introduction

Computational methods play an important role in many areas of dosimetry. They are applied at various length scales encompassing large-scale experimental setups, whole or partial-body representations of the human body down to the microscopic cellular scale and nanometric DNA level. The most widely used techniques are Monte Carlo simulations, but others such as deterministic approaches (e.g., Boltzmann solvers) and unfolding techniques (e.g., to derive neutron energy distributions from experimental data) also play an important role. Apart from their use in the design of experiments and data analysis, computational methods are needed whenever dose or other radiation quantities within the human body are to be evaluated, since their direct (physical) measurement is not feasible (Petoussi-Henss et al., 2010). (Measurements by biological dosimetry also rely on a calibration of the technique, which involves computational determination of absorbed dose.) In the current (and emerging) system of radiological protection, the operation and protection quantities are defined via numerical anthropomorphic phantoms and require

[4] Corresponding author: Hans Rabus, PTB, Abbestrasse 2-12, 10587 Berlin, Germany, hans.rabus@ptb.de

computational simulations for their determination (Endo et al., 2014; Zankl et al., 2018; Endo, 2016).

The move towards personalized medicine implies an important role for patient-specific dosimetry in many areas of radiation medicine, e.g., computed tomography, nuclear radiodiagnostics, and all forms of radiotherapy, where some increasingly used modalities (such as ion beam therapy, FLASH techniques, and molecular radiotherapy) also require modelling of biological factors such as relative biological effectiveness of different radiation qualities and biokinetics of radiopharmaceuticals. In these areas, computational dosimetry is indispensable while becoming increasingly complex when, for example, flexible numerical phantoms of different sizes are used. The latter require approaches beyond the conventionally used voxelized geometries, e.g., tetrahedral mesh phantoms or NURBS phantoms, which have posed challenges to some widely used codes in terms of computational speed (Kim et al., 2016, 2018). These challenges aggravate when real-time computational dosimetry is needed, e.g., to account for motion.

Methodologies based on artificial intelligence such as convoluted neural networks may offer a way to overcome these computational challenges along two different routes. One route is to use neural networks to accelerate radiation transport simulations by training the network to learn time-consuming steps of the simulation and then perform the respective calculations faster based on the learned functional relations. The second route is to train the networks based on Monte Carlo simulation results for a large collection of phantoms with realistic anatomies from a library of contours, organs, etc., and to use then the network for predicting organ doses in real-time from images of patients and information on the exposure (Bottollier-Depois et al., 2020; Harrison et al., 2021).

2. Monte Carlo Radiation Transport Simulation

The Monte Carlo simulation of radiation transport in matter including the detailed modelling of the track structure produced by ionizing particles is based on a theoretical understanding of radiation physics that enables the analogue numerical simulation of radiation interaction processes. In essence, such simulations are numerical evaluations of complicated integrals based on a stochastic sampling approach, where the well-known central limit theorem implies that the result converge to the exact solution of the radiation transport problem (within the limits of approximations that may be applied).

Monte Carlo simulations are widely employed in radiation physics for a variety of applications ranging from the development and characterization of detectors and providing supporting information for data analysis to assessment of individual doses in radiation protection, e.g. in emergency scenarios (Discher et al., 2021). In medical radiation physics, Monte Carlo simulation of particle transport in matter is considered a reference method that is sometimes termed "Monte Carlo gold standard" (Vassiliev et al., 2010; Hoffmann et al., 2018; Mohandass et al., 2018; Stanhope et al., 2018; Milder et al., 2020; Martelli et al., 2021). Monte Carlo simulations are used in this context for the determination or verification of the patient dose distribution in radiotherapy (Sarrut et al., 2014) as well as for assessment of patient radiation doses due to radiation-based medical imaging.

Several general-purpose Monte Carlo codes have been developed that differ in the coverage of particles and energy ranges for which interactions can be modelled and, hence, the number of possible applications (Vassiliev, 2017). Some are stand-alone, turn-key user codes (e. g., the EGS and MCNP families and PHITS) while others are mainly offering toolkits (FLUKA, PENELOPE, GEANT4 family) that require (or enable) the user to tailor the simulation according to the intended purpose. In addition, there exist a number of application-specific Monte Carlo codes that offer better computational performance but require more expertise in their usage. This particularly applies to most track structure codes (Nikjoo et al., 2006). Many of the more generic codes provide advanced graphical user interfaces or templates to facilitate their deployment also by non-expert users.

Generally, results from Monte-Carlo simulations are associated with a statistical uncertainty that decreases inversely with the square root of the number of samples and, hence, with computation time. Simulations of radiation transport in complex geometries therefore can be very CPU time consuming. Examples are cases where many different geometries are involved, such as with "flexible" anthropomorphic phantoms, or where the quantities of interest are scored with high spatial resolution, such as in track structure simulations of biological radiation effects.

A number of approaches have been developed for accelerating Monte Carlo simulations where possible. Traditionally, the most widely used are based on approximations of the simulation problem, e.g. by neglecting processes of minor importance, employing energy or range cut-offs for terminating particle histories or the production of secondary particles, or the use of so-called condensed history approaches where several interactions involving small energy transfers (or small changes in particle direction) are summarized as one artificial event with larger changes of the particles state (Bethe, 1953; Kawrakow et al., 1996; Kawrakow, 1997). Another route employs hybrid approaches where a Monte Carlo simulation of photon transport is coupled with so-called dose kernels describing the dose deposition by electrons (Kling et al., 2001; Papadimitroulas et al., 2012).

In recent years, increased availability of CPU power enabled acceleration approaches by hardware optimization of the simulation codes that exploits the inherent possibility of Monte Carlo approaches for parallelization and calculations using GPU- or cloud-based computations (Badal and Badano, 2009; Ziegenhein et al., 2017; Fernández Bosman et al., 2021). Finally, the application of so-called variance reduction techniques (VRTs) that exploit additional information about the simulation problem (e. g. symmetries, regions of interest) can be very efficient in speeding up simulations (Kawrakow and Fippel, 2000; García-Pareja et al., 2021), but the acceleration is strongly dependent on the actual problem (Sarrut et al., 2021) and the use of VRTs bears the risk of introducing bias so that advanced expertise is required for their application (García-Pareja et al., 2021).

3. Artificial Intelligence and Machine Learning

The term "Artificial Intelligence" (AI) is used in different meanings and standardization organizations are currently trying to set up a framework of generally accepted definitions. It is already consensus, however, that the field of "machine learning" (ML) is a part of AI and that "deep learning" is a sub-field of ML. Machine learning is concerned with computers learning features or correlations from large data sets and making predictions based on this learning process. Deep learning is machine learning using large neural network with many layers. In this report the view of two recent literature reviews related to the use of AI methods in radiotherapy (Arabi and Zaidi, 2020; Sarrut et al., 2021) is adopted that only machine learning is of relevance in these applications and therefore the terms AI and ML are used synonymously.

In machine learning, neural networks are used that consist of an input layer, an output layer, and several hidden layers in between. Depending on the concrete application, the data fed into the input layer can be measurement data, (sets of) images (obtained, e. g. by CT) or information on irradiation parameters (geometry and energy distribution of the radiation source). The data delivered by the network at its output layer can be spectral features, dose maps, source distribution maps or organ segmentations in CT images, and so forth.

Each layer consists of a collection of so-called neurons that are connected to and receive input from (some or all) neurons of the preceding layer. They are also connected and give output to (some or all) neurons in the subsequent layer. The neurons have non-linear (normalized) activation functions and the connections between the neurons are characterized by weighting factors. The number of layers and of neurons per layer, the connections between the neurons, the type of activation function, etc. determine the so-called network architecture, so that naturally a large and still growing variety of different architectures exists. Several software packages based on the PYTHON or MATLAB languages are available that facilitate building and using neural networks.

Typical tasks to be solved by neural networks are regression (where a "best-fit" function is sought) or classification (where a "label" for a data set is sought). Both types involve optimization using a so-called loss function (e.g. the mean squared error) and an initial training of the network based on (ideally large) training data sets that are representative for the type of data encountered in the tasks for which the network is to be used. This training can be supervised learning, where the so-called "ground truth" is known (i.e. the real values of the categories or the functional form of the data), or unsupervised learning, where the data are screened for features.

According to the review by Sarrut et al. (Sarrut et al., 2021), the most commonly used network architectures in the field of radiation dosimetry are Convolutional Neural Networks (CNN) and Generative Adversarial Networks (GAN). Typical applications are detector response modelling (Martinez-Blanco et al., 2016, 2020; Mentzel et al., 2021), CNN-based denoising of low statistics Monte Carlo simulations (Javaid et al., 2019; Peng et al., 2019; Neph et al., 2019; Xu et al., 2019; Javaid et al., 2021), direct dose estimation using CNNs (Sadeghnejad Barkousaraie et al., 2019; Zhang et al., 2019; Bai et al., 2021), and GANs for source and phase space modelling (Sarrut et al., 2019).

The denoising approach features a deep learning-based post-processing of Monte Carlo computations, where the noise in dose maps from the inherent statistical fluctuations is reduced by applying filtering approaches known from data processing or by performing supervised learning of a CNN based on pairs of simulated dose maps with bad and good statistics. According to (Sarrut et al., 2021) one to two orders of magnitude reduction of computation time is possible, but the acceleration depends on the details of the dose distribution to be simulated. Major challenges are the size of the training data sets needed, the generalizability of a trained network to other datasets (e.g. for different treated organs or other treatment modalities) and to ensure that physical boundary conditions (e.g. dose gradients) are respected.

In direct ML-based dose computation, the CNNs are replacing or combined with Monte Carlo simulations. The general idea is to replace computationally expensive parts of the simulations by faster computations with a trained neural network. This involves the generation of large data sets of dose map components by Monte Carlo simulations, which are then used for training and validation of CNNs. So far, this has been mostly used for molecular radiotherapy, shortcutting from PET/CT images to dose distributions without the intermediate step of determining the activity distribution (Arabi and Zaidi, 2020).

In external radiotherapy, the corresponding approach consists in training a CNN to learn the 3D dose map from the 2D fluence map of the radiation source. So far, such approaches are compromised by prediction errors around 10 %, which are too high to meet the uncertainty requirements for dose assessment in external radiotherapy treatment. It is expected, however, that this approach may be useful for applications such as checking the consistency of treatment plans, for a fast comparison of alternative plans or for guiding plan optimization (Sarrut et al., 2021).

In the field of radiation protection dosimetry, AI methods can be useful in all cases where imaging is part of the dose assessment, e.g. in internal dosimetry. They play an important role in accelerated dose computation for personalized (online) dosimetry (Abdelrahman et al., 2020). Another area that in this author's view has a large potential to benefit from machine learning approaches is biological dosimetry and, more generally, cell radiobiology. The rationale for this conjecture is illustrated in Figures 1 and 2.

Figure 1 shows on the left-hand side a picture from an image analysis software where the radiation induced foci (indicating DNA damage repair) have been identified via an image segmentation algorithm. The graph on the right-hand side shows results that are typically obtained from such an analysis, namely the frequency distribution of foci per cell that is obtained by counting the objects classified as foci.

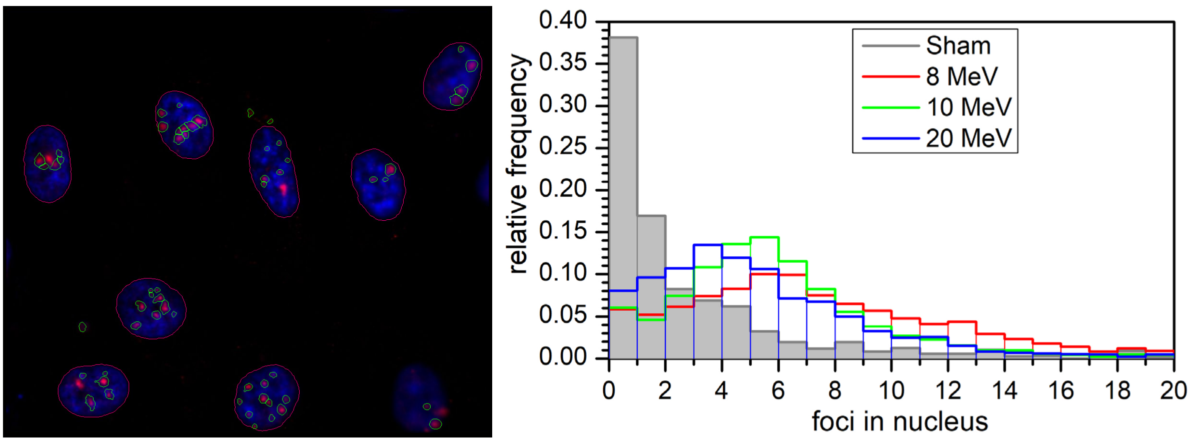

__Figure 1.__ Left: Sample image from a radiobiological foci assay showing radiation-induced foci (small objects outlined by green contour lines) inside cell nuclei (larger objects with blue background outlined by red contour lines). Right: Relative frequency distribution of the number of foci found for cells irradiated with helium ions of different energy (see legend) or unirradiated ("sham"). (Data from (Canhoto, 2018)).

These distributions of the number of foci per cell can then be used to derive, for example, the radiation quality-dependent probability of inducing DNA damage in a cell nucleus by a passing charged particle (Gonon et al., 2019). However, this current state of data analysis does not take into account additional information contained in the analysed images, such as the size of the objects identified as foci (left side of Figure 2), their intensity (right side of Figure 2), the cross-sectional area of the cell nuclei (not shown), etc. All these additional quantitative characteristics could be also used to find differences between foci induced by different radiation qualities or arising spontaneously, analysing the whole multidimensional parameter space in a Big Data approach with machine learning. (The data shown in Figure 2 are only projections of the full data onto one-dimensional variables, which means that some of the information content is lost.)

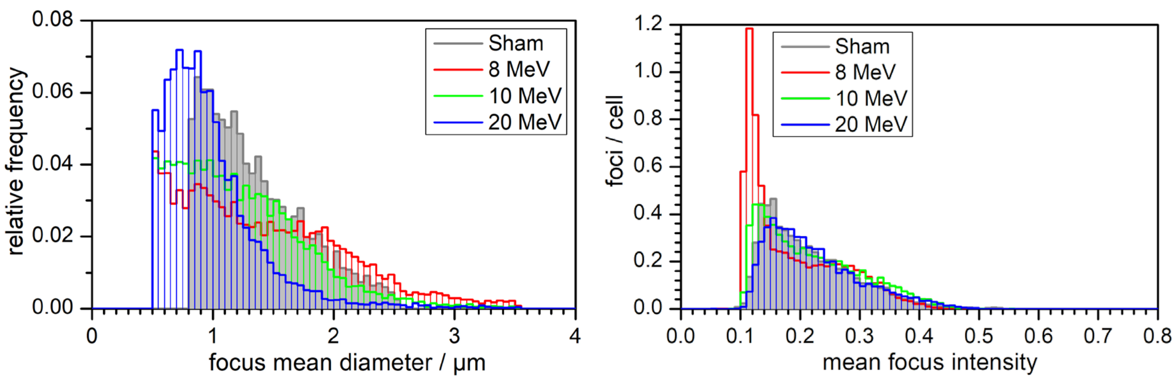

Figure 2. *Left: Relative frequency distribution of the diameter of radiation-induced foci inside the nuclei of cells irradiated with helium ions of different energy (see legend) or unirradiated ("sham"). Right: Frequency distribution of the number of foci per cell with a given average intensity for cells irradiated with helium ions of different energy (see legend) or unirradiated ("sham"). (Data from (Canhoto, 2018)).*

4. Challenges and caveats

4.1 Challenges for AI methods in computational dosimetry

For the use of AI methods in health-related applications, such as in radiation medicine or radiation protection, three AI performance criteria play a particular role that are related to the question of reliability of quantitative predictions: The explainability of results, their associated uncertainties, and the robustness of trained algorithms when confronted with unknown or adversarial input. Development of standardized performance metrics is therefore a prerequisite for the large-scale use of AI methods. Equally important is the availability of evaluated, high quality data sets for training, testing and validation of neural networks.

Aspects of data quality such as homogeneity, representativity, absent or known biases, and known uncertainties are crucial, and the development of quantitative criteria enabling the robust and (ideally) automatic assessment of data quality is urgently needed. In addition, the required size of training, validation and test data sets is considered a bottleneck for the further development of trustworthy AI applications (Sarrut et al., 2021).

Due to restrictions stemming from data privacy, this demand can only be fulfilled with synthetic data sets obtained through numerical simulations. Efficient generation of synthetic data sets through Monte Carlo simulations is therefore also a challenge to be addressed.

In the review paper by (Sarrut et al., 2021), other challenges are mentioned, such as "quantitative" criteria for neural network architecture and hyperparameters. However, these challenges are related to the computer-science aspects of AI and are therefore less relevant for the application of AI in computational dosimetry.

Since the generation of synthetic reference data is vital for the development of trustworthy AI methods, it is also important to keep an eye on the quality of these synthetic data and their reliability. As mentioned earlier, many of the codes used in computational dosimetry have developed to the point where simulations can be performed without advanced expertise. As a result, these simulation tools are being used by an increasing number of researchers, and more and more papers are appearing in the literature in which different studies on similar problems report largely divergent results (e.g., Moradi et al., 2021).

4.2 State of the Art in Computational Dosimetry

Working group 6 "Computational Dosimetry" of the European Radiation Dosimetry Group (EURADOS e.V., www.eurados.org) is devoted to quality assurance in this field and organizes training courses and challenges probing the state of the art of practical application of computational dosimetry techniques (Rabus et al., 2021a). Several comparison exercises have been conducted and the results published (De Saint-Hubert et al., 2021; Eakins et al., 2021; Gómez-Ros et al., 2021; Rabus et al., 2021c, 2021b; Zankl et al., 2021b, 2021c; De Saint-Hubert et al., 2022; Huet et al., 2022; Villagrasa et al., 2022) or submitted for publication in an upcoming virtual special issue of Radiation Measurements dedicated to "EURADOS Intercomparisons in Computational Dosimetry".

The respective exercises covered different areas of computational dosimetry, namely

- Use of ICRP reference computational phantoms for different exposure scenarios (five problems of different complexity)
- Unfolding neutron spectra from Bonner sphere spectrometry (four problems of varying complexity)
- Specific energy and ionization cluster distributions at the (sub)cellular scale for internal emitters (two problems with three and two tasks, respectively)
- Emitted electron spectra and dose enhancement by gold nanoparticles under X-ray irradiation (two problems with four tasks each)

The exercises attracted between a few and a few dozen of participants and were generally carried out in two phases. In the first phase, interested participants were required to solve the published exercise tasks (indicating the problem to be solved and the type of results to be reported). In the second phase, the participants received feedback in the form that their results differed significantly from the reference solution (if applicable) and were invited to check their calculations and send revised results.

In the micro- and nanodosimetry exercises, where the purpose was to compare codes, there was no reference solution, and feedback to participants was based on plausibility checks (Villagrasa et al., 2019; Rabus et al., 2021b; Villagrasa et al., 2022). In the last exercise on the above list, the simulation setup was simple enough (see Figure 3) that participants could be given feedback consisting of specific hints about possible causes for their disagreements.

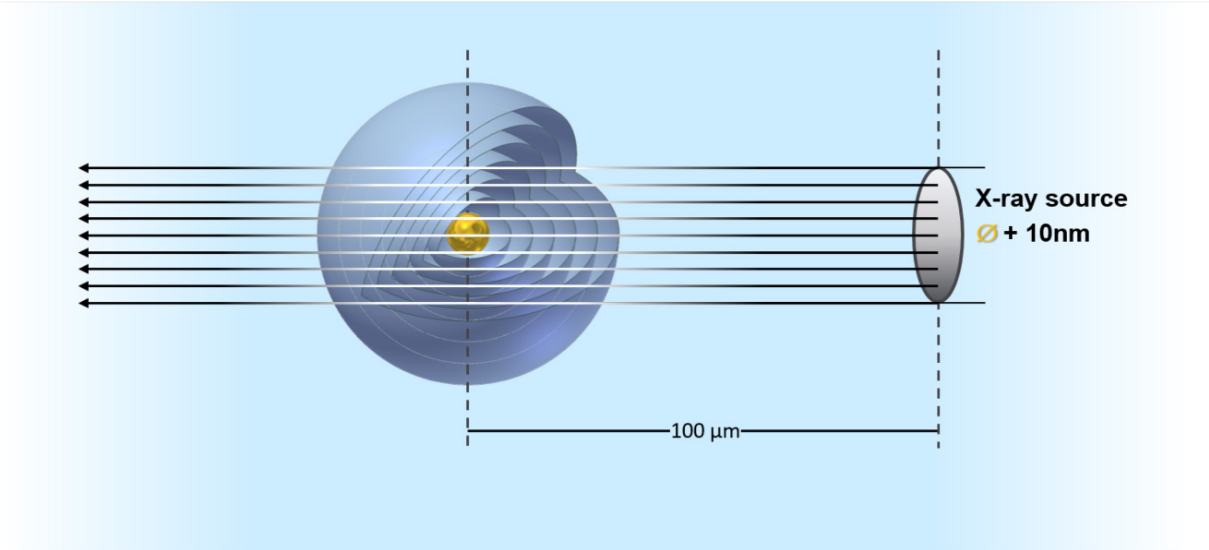

Figure 3. *Schematic illustration of the geometrical setup for the simulations in the exercise on the spectra of emitted electrons and dose enhancement by gold nanoparticles under X-ray irradiation.*

This exercise was particularly remarkable in several respects: first, the exercise definition contained several ambiguities that were noted by some participants who did not seek clarification but rather reported their data without the information that they had noticed the problem and made a choice of what they thought was requested. Second, five out of the ten participants were individuals from code developer groups with long-term expertise or under the supervision of such an expert. In addition, the simplicity of the simulation setup shown in Figure 3 allowed performing comprehensive consistency checks, which revealed that eight participants implemented the exercise tasks incorrectly by using incorrect geometry parameters, incorrect energy spectra, inappropriate tallies, etc. (Rabus et al., 2021b). Finally, none of the participants realized that a straightforward implementation of the simulation setup was lacking secondary charged particle equilibrium, resulting in unrealistic dose enhancement values suggesting orders of magnitude dose enhancement in a biological cell from a single gold nanoparticle (Figure 4). This deficiency could be healed by an approximate correction procedure (Rabus et al., 2021c) to obtain an estimate of the scatter of results between codes, which was the main goal of the exercise. However, the simplicity of the problem would have allowed each participant to obtain a realistic estimate by using a common-random-numbers variance-reduction approach in the simulations.

Compared to the tasks of this exercise, those from the exercises on the use of the ICRP reference computational phantoms in different exposure scenarios were of much higher complexity simply because of the more detailed geometry of the voxel phantoms (Zankl et al., 2021b). The task related to exposure in typical X-ray examinations of the breast and the abdomen involved two interesting aspects of real-word applications (Huet et al., 2022). First, participants had to determine where to position the focus of the X-ray source to obtain an image of the body region with the specified lateral dimensions. Second, the results were to be reported as conversion coefficients to organ absorbed dose from quantities measured in radiation protection quality assurance at real X-ray facilities, namely air kerma and kerma-area-product. (Where the simplification was made that these quantities were to be evaluated in the presence of the phantom.)

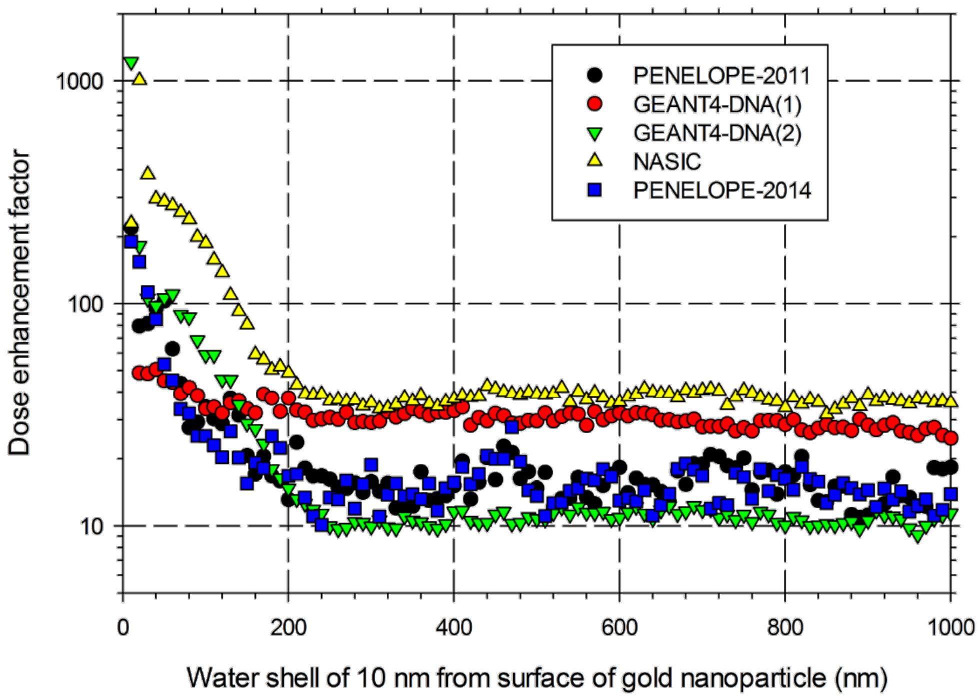

Figure 4. *Sample results reported by participants of the 'nanoparticle exercise' for the dose enhancement in 10-nm spherical shells of water around a 50 nm-diameter gold nanoparticle (Li, 2018). The data (wrongly) suggest that within a sphere of about 2 μm around the nanoparticle the absorbed dose is increased ten to fifty times in the presence of the nanoparticle.*

Of the results reported by participants in the first phase, some were nearly an order of magnitude above or below the reference solution, while the majority agreed with it within a few tens of percent. For the revised solutions, better agreement with the reference solution was generally observed for solutions that were previously extreme outliers, but not as a general trend. In some cases, improvements in values for one target organ were accompanied by greater deviations from the reference value of the revised solution than of the originally reported solution. A detailed discussion of the rather complex compilation of results can be found in (Huet et al., 2022).

In synopsis of all tasks of the ICRP reference phantom exercise, it became evident that, as expected, determining the dose to the bone marrow was challenging for many participants and that the guidelines provided by the ICRP were not always easy to follow. This is why an article explaining the ICRP recommended method for bone marrow dosimetry has also been included in the special issue of Radiation Measurements (Zankl et al., 2021a).

Another article outlining the lessons learned from all the exercises is currently being written. Some of the problems encountered can be summarized as that the users of the code often seem to lack the awareness that the calculated results should be checked for plausibility and that the data obtained from a successful simulation with a well-validated code is not per se correct or physically meaningful. In some of the exercises, there were initially reported results that differed from the reference solution by several orders of magnitude. A common feature of the peer review of the various papers was that these experts saw a need for EURADOS to provide appropriate training courses to promote the competence of code users in computational dosimetry.

5. Conclusions

In summary, methods based on artificial intelligence are also gaining ground in computational radiation dosimetry and offer great potential for future development. To make them trustworthy tools, the generation of large data sets by conventional computational methods (especially Monte Carlo simulation) is required. Many powerful computational tools are available for this purpose, but there are problems in using them: one of them is the availability of computational time and resources. More importantly, however, the ease of use of a code can be deceptive to inexperienced users, and users may not be aware that even in Monte Carlo simulations, explainability (plausibility checks) and uncertainties are important aspects of their computational results.

The mid-term development of computational radiation dosimetry involves a number of ***research and development*** topics that have been described in the recent update of the EURADOS Strategic Research Agenda (Bottollier-Depois et al., 2020; Harrison et al., 2021):

- Development of high-performance Monte Carlo simulations with flexible numerical phantoms
- Exploration and development of machine-learning based techniques for radiation protection dosimetry
- Expanding of the database of cross-section data for different materials at low particle energies for track structure simulations and developing benchmark experiments
- Cross section data for high energy particles, especially neutrons and development of benchmark experiments
- Investigation of mechanisms of radiation action and modelling of biokinetics (including the chemical stage following the radiation interaction)

The introduction of artificial intelligence methods in radiation protection dosimetry holds great potential, but also requires the development of an appropriate ***infrastructure*** in the form of a "reference data hub", i.e. a web platform providing high-quality data sets for training, testing and validating AI algorithms for radiation protection applications. Such a platform must be a sustainable source of reference data sets, continuously fed by data generated in simulations and experiments, and must include a robust data quality-assurance system.

The efficient development of such a data hub also requires ***standardization*** approaches such as harmonized reporting on simulation setups and the data generated. In addition, metrics for assessing computational data quality need to be developed, and ways to improve good practices by offering certification schemes for code users should be explored.

Finally, the above developments must be accompanied by ***education and training*** (E&T) activities on good scientific practices in simulations and in the use of artificial intelligence methods. Such E&T activities need to be carried out on a larger scale than the training courses organized by volunteers within their engagement in EURADOS (Alves et al., 2019), in order to reach a larger part of the community of radiation protection experts and researchers and to build a solid foundation for the future of radiation protection in Europe.

6. References

Abdelrahman, M., Lombardo, P., Vanhavere, F., Seret, A., Phillips, C., Covens, P., 2020. First steps towards online personal dosimetry using computational methods in interventional radiology: Operator's position tracking and simulation input generation. Radiation Physics and Chemistry 171, 108702. https://doi.org/10.1016/j.radphyschem.2020.108702

Alves, J.G., Fantuzzi, E., Ruehm, W., Gilvin, P., Vargas, A., Tanner, R.J., Rabus, H., Ponte, M.A.L., Breustedt, B., Harrison, R.M., Stolarczyk, L., Fattibene, P., Woda, C., Caresana, M., Knežević, Ž., Bottollier-Depois, J.-F., Clairand, I., Mayer, S., Miljanic, S., Olko, P., Schuhmacher, H., Stadtmann, H., Vanhavere, F., 2019. EURADOS education and training activities. J. Radiol. Prot. 39, R37–R50. https://doi.org/10.1088/1361-6498/ab3256

Arabi, H., Zaidi, H., 2020. Applications of artificial intelligence and deep learning in molecular imaging and radiotherapy. European J Hybrid Imaging 4, 17. https://doi.org/10.1186/s41824-020-00086-8

Badal, A., Badano, A., 2009. Accelerating Monte Carlo simulations of photon transport in a voxelized geometry using a massively parallel graphics processing unit. Medical Physics 36, 4878–4880. https://doi.org/10.1118/1.3231824

Bai, T., Wang, B., Nguyen, D., Jiang, S., 2021. Deep dose plugin: towards real-time Monte Carlo dose calculation through a deep learning-based denoising algorithm. Mach. Learn.: Sci. Technol. 2, 025033. https://doi.org/10.1088/2632-2153/abdbfe

Bethe, H.A., 1953. Molière's Theory of Multiple Scattering. Phys. Rev. 89, 1256–1266. https://doi.org/10.1103/PhysRev.89.1256

Bottollier-Depois, J.-F., Clairand, I., Fantuzzi, E., Fattibene, P., Harrison, R., Hupe, O., Olko, P., Olšovcová, V., Rühm, W., Silari, M., Tanner, R., Vanhavere, F., 2020. Visions for Radiation Dosimetry over the Next Two Decades - Strategic Research Agenda of the European Radiation Dosimetry Group: Version 2020. Neuherberg, Germany.

Canhoto, J., 2018. LET- and Radiation Quality-dependence of the complexity of DNA damage (Master Thesis). Universidade de Lisboa, Lisbon.

De Saint-Hubert, M., Farah, J., Klodowska, M., Romero-Expósito, M.T., Tyminska, K., Mares, V., Olko, P., Stolarczyk, L., Trinkl, S., 2022. The influence of nuclear models and Monte Carlo radiation transport codes on stray neutron dose estimations in proton therapy. Radiation Measurements 150, 106693. https://doi.org/10.1016/j.radmeas.2021.106693

De Saint-Hubert, M., Tymińska, K., Stolarczyk, L., Brkić, H., 2021. Fetus dose calculation during proton therapy of pregnant phantoms using MCNPX and MCNP6.2 codes. Radiation Measurements 149, 106665. https://doi.org/10.1016/j.radmeas.2021.106665

Discher, M., Eakins, J., Woda, C., Tanner, R., 2021. Translation of the absorbed dose in the mobile phone to organ doses of an ICRP voxel phantom using MCNPX simulation of an Ir-192 point source. Radiation Measurements 146, 106603. https://doi.org/10.1016/j.radmeas.2021.106603

Eakins, J., Huet, C., Brkić, H., Capello, K., Desorgher, L., Epstein, L., Hunt, J.G., Kim, H.S., Krstic, D., Lee, Y.-K., Manohari, M., Nikezic, D., Shukrun, R.H., Souza-Santos, D., Tymińska, K., 2021. Monte Carlo calculation of organ and effective dose rates from ground contaminated by Am-241: Results of an international intercomparison exercise. Radiation Measurements 148, 106649. https://doi.org/10.1016/j.radmeas.2021.106649

Endo, A., 2016. Operational quantities and new approach by ICRU. Ann ICRP 45, 178–187. https://doi.org/10.1177/0146645315624341

Endo, A., Petoussi-Henss, N., Zankl, M., Bolch, W.E., Eckerman, K.F., Hertel, N.E., Hunt, J.G., Pelliccioni, M., Schlattl, H., Menzel, H.-G., 2014. Overview of the ICRP/ICRU adult reference computational phantoms and dose conversion coefficients for external idealised exposures. Radiation Protection Dosimetry 161, 11–16. https://doi.org/10.1093/rpd/nct304

Fernández Bosman, D., García Balcaza, V., Delgado, C., Principi, S., Duch, M.A., Ginjaume, M., 2021. Validation of the MC-GPU Monte Carlo code against the PENELOPE/penEasy code system and benchmarking against experimental conditions for typical radiation qualities and setups in interventional radiology and cardiology. Physica Medica 82, 64–71. https://doi.org/10.1016/j.ejmp.2021.01.075

García-Pareja, S., Lallena, A.M., Salvat, F., 2021. Variance-Reduction Methods for Monte Carlo Simulation of Radiation Transport. Front. Phys. 9, 718873. https://doi.org/10.3389/fphy.2021.718873

Gómez-Ros, J.M., Moraleda, M., Arce, P., Bui, D.-K., Dang, T.-M.-L., Desorgher, L., Kim, H.S., Krstic, D., Kuć, M., Le, N.-T., Lee, Y.-K., Nguyen, N.-Q., Nikezic, D., Tymińska, K., Vrba, T., 2021. Monte Carlo calculation of the organ equivalent dose and effective dose due to immersion in a 16N beta source in air using the ICRP reference phantoms. Radiation Measurements 145, 106612. https://doi.org/10.1016/j.radmeas.2021.106612

Gonon, G., Villagrasa, C., Voisin, P., Meylan, S., Bueno, M., Benadjaoud, M.A., Tang, N., Langner, F., Rabus, H., Barquinero, J.-F., Giesen, U., Gruel, G., 2019. From Energy Deposition of Ionizing Radiation to Cell Damage Signaling: Benchmarking Simulations by Measured Yields of Initial DNA Damage after Ion Microbeam Irradiation. Radiat. Res. 191, 566–584. https://doi.org/10.1667/RR15312.1

Harrison, R.M., Ainsbury, E., Alves, J., Bottollier-Depois, J.-F., Breustedt, B., Caresana, M., Clairand, I., Fantuzzi, E., Fattibene, P., Gilvin, P., Hupe, O., Knežević, Ž., Lopez, M.A., Olko, P., Olšovcová, V., Rabus, H., Rühm, W., Silari, M., Stolarczyk, L., Tanner, R., Vanhavere, F., Vargas, A., Woda, C., 2021. Eurados Strategic Research Agenda 2020: Vision for the Dosimetry of Ionising Radiation. Radiat. Prot. Dosim. 194, 42–56. https://doi.org/10.1093/rpd/ncab063

Hoffmann, L., Alber, M., Söhn, M., Elstrøm, U.V., 2018. Validation of the Acuros XB dose calculation algorithm versus Monte Carlo for clinical treatment plans. Med. Phys. 45, 3909–3915. https://doi.org/10.1002/mp.13053

Huet, C., Eakins, J., Zankl, M., Gómez-Ros, J.M., Jansen, J., Moraleda, M., Struelens, L., Akar, D.K., Borbinha, J., Brkić, H., Bui, D.K., Capello, K., Linh Dang, T.M., Desorgher, L., Di Maria, S., Epstein, L., Faj, D., Fantinova, K., Ferrari, P., Gossio, S., Hunt, J., Jovanovic, Z., Kim, H.S., Krstic, D., Le, N.T., Lee, Y.-K., Murugan, M., Nadar, M.Y., Nguyen, N.-Q., Nikezic, D., Patni, H.K., Santos, D.S., Tremblay, M., Trivino, S., Tymińska, K., 2022. Monte Carlo calculation of organ and effective doses due to photon and neutron point sources and typical X-ray examinations: Results of an international intercomparison exercise. Radiation Measurements 150, 106695. https://doi.org/10.1016/j.radmeas.2021.106695

Javaid, U., Souris, K., Dasnoy, D., Huang, S., Lee, J.A., 2019. Mitigating inherent noise in Monte Carlo dose distributions using dilated U-Net. Medical Physics 46, 5790–5798. https://doi.org/10.1002/mp.13856

Javaid, U., Souris, K., Huang, S., Lee, J.A., 2021. Denoising proton therapy Monte Carlo dose distributions in multiple tumor sites: A comparative neural networks architecture study. Physica Medica 89, 93–103. https://doi.org/10.1016/j.ejmp.2021.07.022

Kawrakow, I., 1997. Improved modeling of multiple scattering in the Voxel Monte Carlo model. Med. Phys. 24, 505–517. https://doi.org/10.1118/1.597933

Kawrakow, I., Fippel, M., 2000. Investigation of variance reduction techniques for Monte Carlo photon dose calculation using XVMC. Phys. Med. Biol. 45, 2163–2183. https://doi.org/10.1088/0031-9155/45/8/308

Kawrakow, I., Fippel, M., Friedrich, K., 1996. 3D electron dose calculation using a Voxel based Monte Carlo algorithm (VMC). Med. Phys. 23, 445–457. https://doi.org/10.1118/1.597673

Kim, C.H., Yeom, Y.S., Nguyen, T.T., Han, M.C., Choi, C., Lee, H., Han, H., Shin, B., Lee, J.-K., Kim, H.S., Zankl, M., Petoussi-Henss, N., Bolch, W.E., Lee, C., Chung, B.S., Qiu, R., Eckerman, K., 2018. New mesh-type phantoms and their dosimetric applications, including emergencies. Ann ICRP 47, 45–62. https://doi.org/10.1177/0146645318756231

Kim, C.H., Yeom, Y.S., Nguyen, T.T., Wang, Z.J., Kim, H.S., Han, M.C., Lee, J.K., Zankl, M., Petoussi-Henss, N., Bolch, W.E., Lee, C., Chung, B.S., 2016. The reference phantoms: voxel vs polygon. Ann ICRP 45, 188–201. https://doi.org/10.1177/0146645315626036

Kling, A., Barão, F.J.C., Nakagawa, M., Távora, L., Vaz, P. (Eds.), 2001. Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proceedings of the Monte Carlo 2000 Conference, Lisbon, 23–26 October 2000. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-18211-2

Li, W.B., 2018. Nanoparticle exercise. Presented at the EURADOS Annual Meeting 2018.

Martelli, F., Tommasi, F., Sassaroli, A., Fini, L., Cavalieri, S., 2021. Verification method of Monte Carlo codes for transport processes with arbitrary accuracy. Sci Rep 11, 19486. https://doi.org/10.1038/s41598-021-98429-3

Martinez-Blanco, Ma. del R., Ornelas-Vargas, G., Castañeda-Miranda, C.L., Solís-Sánchez, L.O., Castañeda-Miranada, R., Vega-Carrillo, H.R., Celaya-Padilla, J.M., Garza-Veloz, I., Martínez-Fierro, M., Ortiz-Rodríguez, J.M., 2016. A neutron spectrum unfolding code based on generalized regression artificial neural networks. Applied Radiation and Isotopes 117, 8–14. https://doi.org/10.1016/j.apradiso.2016.04.029

Martinez-Blanco, Ma., Serrano-Muñoz, A., Vega-Carrillo, H., de Sousa-Lacerda, M., Mendez-Villafañe, R., Gallego, E., de Santiago, A., Solis-Sanchez, L., Ortiz-Rodriguez, J., 2020. Synapse. A Neutron Spectrum Unfolding Code Based on Generalized Regression Artificial Neural Networks. EAI Endorsed Transactions on Industrial Networks and Intelligent Systems 7, 166667. https://doi.org/10.4108/eai.21-10-2020.166667

Mentzel, F., Derugin, E., Jansen, H., Kröninger, K., Nackenhorst, O., Walbersloh, J., Weingarten, J., 2021. No more glowing in the dark: how deep learning improves exposure date estimation in thermoluminescence dosimetry. J. Radiol. Prot. 41, S506–S521. https://doi.org/10.1088/1361-6498/ac20ae

Milder, M.T.W., Alber, M., Söhn, M., Hoogeman, M.S., 2020. Commissioning and clinical implementation of the first commercial independent Monte Carlo 3D dose calculation to replace CyberKnife M6TM patient-specific QA measurements. J. Appl. Clin. Med. Phys. 21, 304–311. https://doi.org/10.1002/acm2.13046

Mohandass, P., Khanna, D., Manigandan, D., Bhalla, N.K., Puri, A., 2018. Validation of a Software Upgrade in a Monte Carlo Treatment Planning System by Comparison of Plans in Different Versions. J Med Phys 43, 93–99. https://doi.org/10.4103/jmp.JMP_7_18

Moradi, F., Saraee, K.R.E., Sani, S.F.A., Bradley, D.A., 2021. Metallic nanoparticle radiosensitization: The role of Monte Carlo simulations towards progress. Radiation Physics and Chemistry 180, 109294. https://doi.org/10.1016/j.radphyschem.2020.109294

Neph, R., Huang, Y., Yang, Y., Sheng, K., 2019. DeepMCDose: A Deep Learning Method for Efficient Monte Carlo Beamlet Dose Calculation by Predictive Denoising in MR-Guided Radiotherapy, in: Nguyen, D., Xing, L., Jiang, S. (Eds.), Artificial Intelligence in Radiation Therapy, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 137–145. https://doi.org/10.1007/978-3-030-32486-5_17

Nikjoo, H., Uehara, S., Emfietzoglou, D., Cucinotta, F.A., 2006. Track-structure codes in radiation research. Radiation Measurements 41, 1052–1074. https://doi.org/10.1016/j.radmeas.2006.02.001

Papadimitroulas, P., Loudos, G., Nikiforidis, G.C., Kagadis, G.C., 2012. A dose point kernel database using GATE Monte Carlo simulation toolkit for nuclear medicine applications: Comparison with other Monte Carlo codes: Dose point kernels. Med. Phys. 39, 5238–5247. https://doi.org/10.1118/1.4737096

Peng, Z., Shan, H., Liu, T., Pei, X., Wang, G., Xu, X.G., 2019. MCDNet – A Denoising Convolutional Neural Network to Accelerate Monte Carlo Radiation Transport Simulations: A Proof of Principle With Patient Dose From X-Ray CT Imaging. IEEE Access 7, 76680–76689. https://doi.org/10.1109/ACCESS.2019.2921013

Petoussi-Henss, N., Bolch, W.E., Eckerman, K.F., Endo, A., Hertel, N., Hunt, J., Pelliccioni, M., Schlattl, H., Zankl, M., on Radiological Protection, I.C., on Radiation Units, I.C., Measurements, 2010. ICRP Publication 116. Conversion coefficients for radiological protection quantities for external radiation exposures. Annals of the ICRP 40, 1–257. https://doi.org/10.1016/j.icrp.2011.10.001

Rabus, H., Gómez-Ros, J.M., Villagrasa, C., Eakins, J., Vrba, T., Blideanu, V., Zankl, M., Tanner, R., Struelens, L., Brkić, H., Domingo, C., Baiocco, G., Caccia, B., Huet, C., Ferrari, P., 2021a. Quality assurance for the use of computational methods in dosimetry: activities of EURADOS Working Group 6 `Computational Dosimetry'. J. Radiol. Prot. 41, 46–58. https://doi.org/10.1088/1361-6498/abd914

Rabus, H., Li, W.B., Nettelbeck, H., Schuemann, J., Villagrasa, C., Beuve, M., Di Maria, S., Heide, B., Klapproth, A.P., Poignant, F., Qiu, R., Rudek, B., 2021b. Consistency checks of results from a Monte Carlo code intercomparison for emitted electron spectra and energy deposition around a single gold nanoparticle irradiated by X-rays. Radiat. Meas. 147, 106637. https://doi.org/10.1016/j.radmeas.2021.106637

Rabus, H., Li, W.B., Villagrasa, C., Schuemann, J., Hepperle, P.A., Rosales, L. de la F., Beuve, M., Maria, S.D., Klapproth, A.P., Li, C.Y., Poignant, F., Rudek, B., Nettelbeck, H., 2021c. Intercomparison of Monte Carlo calculated dose enhancement ratios for gold nanoparticles irradiated by X-rays: Assessing the uncertainty and correct methodology for extended beams. Phys. Medica 84, 241–253. https://doi.org/10.1016/j.ejmp.2021.03.005

Sadeghnejad Barkousaraie, A., Ogunmolu, O., Jiang, S., Nguyen, D., 2019. Using Supervised Learning and Guided Monte Carlo Tree Search for Beam Orientation Optimization in Radiation Therapy, in: Nguyen, D., Xing, L., Jiang, S. (Eds.), Artificial Intelligence in Radiation Therapy, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 1–9. https://doi.org/10.1007/978-3-030-32486-5_1

Sarrut, D., Bardiès, M., Boussion, N., Freud, N., Jan, S., Létang, J.-M., Loudos, G., Maigne, L., Marcatili, S., Mauxion, T., Papadimitroulas, P., Perrot, Y., Pietrzyk, U., Robert, C., Schaart, D.R., Visvikis, D., Buvat, I., 2014. A review of the use and potential of the

GATE Monte Carlo simulation code for radiation therapy and dosimetry applications: GATE for dosimetry. Med. Phys. 41, 064301. https://doi.org/10.1118/1.4871617

Sarrut, D., Etxebeste, A., Muñoz, E., Krah, N., Létang, J.M., 2021. Artificial Intelligence for Monte Carlo Simulation in Medical Physics. Front. Phys. 9, 738112. https://doi.org/10.3389/fphy.2021.738112

Sarrut, D., Krah, N., Létang, J.M., 2019. Generative adversarial networks (GAN) for compact beam source modelling in Monte Carlo simulations. Phys. Med. Biol. 64, 215004. https://doi.org/10.1088/1361-6560/ab3fc1

Stanhope, C.W., Drake, D.G., Liang, J., Alber, M., Söhn, M., Habib, C., Willcut, V., Yan, D., 2018. Evaluation of machine log files/ MC -based treatment planning and delivery QA as compared to Arc CHECK QA. Med. Phys. 45, 2864–2874. https://doi.org/10.1002/mp.12926

Vassiliev, O.N., 2017. Monte Carlo Methods for Radiation Transport, Biological and Medical Physics, Biomedical Engineering. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-44141-2

Vassiliev, O.N., Wareing, T.A., McGhee, J., Failla, G., Salehpour, M.R., Mourtada, F., 2010. Validation of a new grid-based Boltzmann equation solver for dose calculation in radiotherapy with photon beams. Phys. Med. Biol. 55, 581–598. https://doi.org/10.1088/0031-9155/55/3/002

Villagrasa, C., Bordage, M.-C., Bueno, M., Bug, M., Chiriotti, S., Gargioni, E., Heide, B., Nettelbeck, H., Parisi, A., Rabus, H., 2019. Assessing the contribution of cross-sections to the uncertainty of Monte Carlo calculations in micro- and nanodosimetry. Radiat. Prot. Dosim. 183, 11–16. https://doi.org/10.1093/rpd/ncy240

Villagrasa, C., Rabus, H., Baiocco, G., Perrot, Y., Parisi, A., Struelens, L., Qiu, R., Beuve, M., Poignant, F., Pietrzak, M., Nettelbeck, H., 2022. Intercomparison of micro- and nanodosimetry Monte Carlo simulations: An approach to assess the influence of different cross-sections for low-energy electrons on the dispersion of results. Radiation Measurements 150, 106675. https://doi.org/10.1016/j.radmeas.2021.106675

Xu, B., Zhang, J., Wang, R., Xu, K., Yang, Y.-L., Li, C., Tang, R., 2019. Adversarial Monte Carlo denoising with conditioned auxiliary feature modulation. ACM Trans. Graph. 38, 1–12. https://doi.org/10.1145/3355089.3356547

Zankl, M., Becker, J., Lee, C., Bolch, W.E., Yeom, Y.S., Kim, C.H., 2018. Computational phantoms, ICRP/ICRU, and further developments. Ann ICRP 47, 35–44. https://doi.org/10.1177/0146645318756229

Zankl, M., Eakins, J., Gómez Ros, J.-M., Huet, C., 2021a. The ICRP recommended methods of red bone marrow dosimetry. Radiation Measurements 146, 106611. https://doi.org/10.1016/j.radmeas.2021.106611

Zankl, M., Eakins, J., Gómez Ros, J.-M., Huet, C., Jansen, J., Moraleda, M., Reichelt, U., Struelens, L., Vrba, T., 2021b. EURADOS intercomparison on the usage of the ICRP/ICRU adult reference computational phantoms. Radiation Measurements 145, 106596. https://doi.org/10.1016/j.radmeas.2021.106596

Zankl, M., Gómez Ros, J.-M., Moraleda, M., Reichelt, U., Akar, D.K., Borbinha, J., Desorgher, L., Di Maria, S., EL Bakkali, J., Fantinova, K., Ferrari, P., Gossio, S., Hunt, J., Jovanovic, Z., Kim, H.S., Krstic, D., Lee, Y.-K., Nadar, M.Y., Nikezic, D., Patni, H.K., Murugan, M., Triviño, S., 2021c. Monte Carlo calculation of organ dose coefficients for internal dosimetry: Results of an international intercomparison exercise. Radiation Measurements 148, 106661. https://doi.org/10.1016/j.radmeas.2021.106661

Zhang, J., Liu, S., Li, T., Mao, R., Du, C., Liu, J., 2019. Voxel-Level Radiotherapy Dose Prediction Using Densely Connected Network with Dilated Convolutions, in: Nguyen, D., Xing, L., Jiang, S. (Eds.), Artificial Intelligence in Radiation Therapy, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 70–77. https://doi.org/10.1007/978-3-030-32486-5_9

Ziegenhein, P., Kozin, I.N., Kamerling, C.P., Oelfke, U., 2017. Towards real-time photon Monte Carlo dose calculation in the cloud. Phys. Med. Biol. 62, 4375–4389. https://doi.org/10.1088/1361-6560/aa5d4e

Roundtable presentation - ICRU Report 95: Operational Quantities for External Radiation Exposure

Thomas Otto[5]

ICRU and CERN, Geneva, Switzerland

In 2020, the International Commission on Radiation Units and Measurements published ICRU Report 95 [1] on revised operational quantities for the dosimetry of external radiation. What is the motivation and what will be the consequences for radiation protection of this change?

ICRP has defined in its Publication 103 [2] a set of protection quantities, to estimate radiation risk for "small" doses for the purpose of radiation protection. The present contribution deals only with effective dose *E* for whole-body exposure, although the scope of ICRU Report 95 includes also quantities for partial body exposure. Due to its definition over the volume of the body, *E* is not measurable, and ICRU has introduced operational quantities which are defined in a single point and which shall give an estimate of the protection quantity. In ICRU Reports 39 [3] and 51 [4], the presently valid operational quantities were defined and in ICRU Report 57 [5] and ICRP Publication 74 [6], conversion coefficients for physical quantities describing the radiation field were published. The quantities and conversion coefficients were defined with help of simple geometrical bodies as phantoms and a quality function depending on unrestricted LET, $Q(L)$. The operational quantities for whole-body exposure, $H^*(10)$ for ambient dosimetry and $H_p(10)$ for personal dosimetry, give good estimates of the effective dose *E* in radiation fields encountered in nuclear industry, the mainstay of radiation protection at the time of their introduction. However, significant over- or underestimate of *E* at very high energies, for example at accelerators, and at very low photon energies, as in certain medial applications, were observed [7].

ICRU Report 95 aligns the new operational quantities with effective dose *E*, using the same phantoms and the same radiation weighting factor w_R in their definition. With this change, the new quantities H^* for ambient dosimetry and H_p for personal dosimetry now follow closely the energy dependence of effective dose *E*, having often identical numerical values. Conversion coefficients for the new quantities are published for a wide range of energies and particles, covering the needs of all fields where ionising radiation is applied.

The introduction of the new operational quantities, which is not expected before the publication of the next Basic Recommendations of the ICRP in the 2030s, will obviously have consequences for the measurement of ionising radiation. So far, only a few sectors have been analysed, more studies should be undertaken.

In radiation fields from activation products, dominated by photons with energies from 50 keV to 3 MeV, the quantities H^* or H_p will have a numerical value of 85 % of the

[5] Corresponding author: Thomas Otto, ICRU and CERN, 1211 Geneva 23, Switzerland, CERN, Thomas.Otto@cern.ch

corresponding value of the present operational quantities. In radiation fields dominated by electrons one can expect higher numerical values by a factor of two. In interventional radiology, the medical personnel is exposed to photons backscattered from the patient at low energies, here a reduction of the measured values by a factor 2 can be estimated.

The values of operational quantities in radiation fields generated during the operation of accelerators will fall within approximately ±20 % of present values, depending on direction to the source and thickness of the shielding. This observation does not call for changes in either constructive or operational radiation protection.

Photon dosimeters for the measurement of ambient dose rates $H^*(10)$ can be recalibrated for the quantity H^* because their sensitivity is cut-off at about 50 keV [8]. Personal dosimeters sensitive to photons with energies as low as 15 keV would show a significant overestimation of H_p in the low-energy range [9], [10]. A redesign of their evaluation algorithm (for multiple-detector types) or their filter package (for single-detector types) is necessary [11]. Rem-counters will continue to give a reasonable estimate of ambient dose rates H^* from neutrons after a slight re-calibration [12].

National dose registers record values of effective dose for occupationally exposed workers. Normally, measured values of $H_p(10)$ are entered in these records as a surrogate for E since an more precise estimate would be far too costly to obtain. The introduction of H_p would lead to a better estimation of effective dose. For most monitored persons, having zero or very small doses in one monitoring period, no individual change would occur. One can expect the collective dose measured by personal dosimeters to result in a slightly lower value due to the ratio $H_p/H_p(10) < 1$ as described above. For flying personnel, no change would happen, as values of E are calculated with models without using dosimeters.

In conclusion, the operational quantities for the dosimetry of external radiation introduced by ICRU in Report 95 will

- lead to a simplification of the system of quantities, by using similar definitions and the same phantoms for protection and operational quantities
- result in modified measured values of the operational quantities in workplace radiation fields, usually too small to warrant big changes in radiation protection practice
- require a revision of individual dosimeters for photons, while ambient dosimeters for photons and neutrons can be simply recalibrated
- should improve the quality of recorded dose values in national registers due to the improved approximation of E

All areas highlighted here will require more research and development. The introduction of the new quantities, scheduled sometime after the next Basic Recommendations of ICRP, leaves more than 10 years for this work.

References

[1]. International Commission on Radiation Units and Measurements, ICRU Report 95 Operational quantities for External Radiation Exposure, (ICRU, Bethesda) (2020).

[2]. International Commission on Radiological Protection, ICRP Publication 103, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP (Elsevier Science, Oxford) (2007).

[3]. International Commission on Radiation Units and Measurements. ICRU Report 39 Determination of Dose Equivalents Resulting from External Radiation Sources, (ICRU, Bethesda) (1985).

[4]. International Commission on Radiation Units and Measurements, ICRU Report 51, Quantities and Units in Radiation Protection Dosimetry, (ICRU, Bethesda) (1993).

[5]. International Commission on Radiation Units and Measurements, ICRU Report 57, Conversion Coefficients for Use in Radiological Protection against External Radiation, (ICRU, Bethesda) (1998).

[6]. International Commission on Radiological Protection, ICRP Publication 74, Conversion Coefficients for Use in Radiological Protection against External Radiation, (Elsevier Science, Oxford) (1996).

[7]. Otto, T. et al., The ICRU Proposal for New Operational Quantities for External Radiation, Rad. Prot. Dosim.), 180 10–16 (2018).

[8]. Otto, T., Response of Photon Dosimeters and Survey Instruments to New Operational Quantities Proposed by ICRU RC 26, Journal of Instrumentation 14 P01010 (2019).

[9]. Eakins, J. S., and Tanner, R.J., The effects of a revised operational dose quantity on the response characteristics of a β/γ personal dosemeter. J. Radiol. Prot. 39 399-421 (2018).

[10]. Caresana M. et al., Impact of new operational dosimetric quantities on individual monitoring services, J. Radiol. Prot. 41 1110 (2021).

[11]. Hoedlmoser, H., Bandalo, V., Figel, M., BeOSL dosemeters and new ICRU operational quantities: Response of existing dosemeters and modification options, Rad. Meas. 139 (2020) 106482

[12]. Eakins, J. S., Tanner, R.J., and Hager, L.H., The effect of a revised operational dose quantity on the response characteristics of neutron survey instruments. J. Radiol. Prot. 38 688-701 (2018).

Roundtable presentation - New Operational Quantities for External Radiation Exposure: EURADOS Impact Evaluation

Phil Gilvin[6]

UK Health Security Agency, Chilton, Didcot, OXON OX11 0RQ, U.K. on behalf of the EURADOS task group on the impact evaluation of the new operational quantities

Context

In December 2020, the International Commission on Radiation Units and Measurements defined new operational dose quantities for assessing external radiation exposure[7], replacing those that were defined in a series of reports in the late 1980s and early 1990s and have been in use since then.

For over a quarter of a century EURADOS (www.eurados.org), now a network of over 80 institutions, has helped to advance the understanding and application of dosimetry for ionising radiation. As part of this remit, EURADOS is now preparing an initial evaluation[8] of the new operational quantities. The work began in 2019 and drew upon expertise from across the various EURADOS working groups, also benefitting from dialogue with the ICRU project team. The EURADOS report is at an advanced stage and will be published with free access on the website during 2022.

The report covers the implications of the new operational quantities for:

- dosemeter and instrument design
- radiation protection practices
- calibration and reference fields
- international standards
- regulation and dose registries.

We give here an overview of the main points and conclusions.

Benefits of New Quantities

The new quantities provide an improved representation of the protection quantities, and hence of detriment. They are defined for a wider range of radiation types and for an increased range of energies, and therefore can be applied at higher energies than the

[6] Corresponding author: Phil Gilvin, UK Health Security Agency, Chilton, Didcot, OXON OX11 0RQ, U.K., Phil.Gilvin@ukhsa.gov.uk

[7] ICRU Report 95: “Operational Quantities for External Radiation Exposure”

[8] “Evaluation of the Impact of the New ICRU Operational Quantities and Recommendations for their Practical Application”

current quantities. This is important in high-energy fields such as those encountered around particle accelerators, including proton therapy units.

The new definitions also correct a deficiency in the current quantities which leads to significant overestimation of the protection quantities in the photon energy range below about 80 keV, the range in which doses are incurred from modern medical diagnostic and interventional procedures.

Main conclusions

Devices (Instruments and Dosemeters)

In order to assess the new quantities with acceptable accuracy, many instruments and dosemeters will need a measure of redesign. In some cases the redesign will be minimal, but in others it will be radical and costly. For some existing types of dosemeter the required redesign may be impractical or impossible.

Possible adaptations

The devices affected include hand-held survey instruments of varying complexity; active ("electronic") personal dosemeters; and passive personal dosemeters. Both active and passive personal dosemeters may have single or multiple sensitive elements.

The range of possible redesign or adaptations is as follows.

a) simple re-calibration, so that the instrument reads differently for the new quantities,

b) using a different reference radiation energy for calibration, to balance positive and negative deviations,

c) change of dose calculation algorithm,

d) physical changes, e.g. to the shape and composition of filters/ filter packs.

Adaptations (a) - (c) are unlikely to be effective, on their own, for many instruments or dosemeters. It is more likely that a combination of (a) – (c) with (d) will be needed. Problems are likely to be greater for simpler dosemeters.

An example of where significant problems may arise is for the simple thermoluminescence dosemeters that use "conventional" lithium fluoride, LiF (Mg, Ti). In the photon energy range below about 80 keV, this material already over-responds in terms of the current operational quantities. Its over-response in terms of the new ones will be worse.

Measurement Uncertainties

For most devices, energy dependence of response is one of the main sources of measurement uncertainty. Because the change to the new quantities will affect energy dependence of response, measurement uncertainties will certainly be affected.

For photons – which account for the bulk of collective occupational exposures – the picture is complicated by the fact that the primary set of conversion coefficients published in ICRU 95 require conditions that cannot be realised in calibration and testing laboratories. ICRU

95 also includes a secondary set, which require conditions ("charged particle equilibrium", CPE) that do allow for repeatable laboratory measurements to be made.

Considering the new quantities when calculated with the primary ("full transport") conversion coefficients, the variation with photon energy is greater than for the current quantities. This would make it likely that measurement uncertainties would be significantly greater for the new quantities than the old, even following design changes.

However, because it will be necessary to use the secondary, CPE, set of conversion coefficients, it is possible that current magnitudes of measurement uncertainty can be maintained. Further work is needed here.

Spreading of Costs

It is noted that because there will be a long transition period, the costs of changing to the new quantities can be spread over time. This is especially true for international standards and similar documents (see below), which periodically undergo regular review. In this case, the new quantities can be dealt with as part of the routine review process, although they will of course make the review significantly more extensive.

For devices, however, a very long transition period is impractical. Instrument manufacturers, for instance, could switch to producing "new-quantity" versions on an announced date; but they will still need to maintain "old-quantity" versions and for some time they will need to cater for both. Individual monitoring services can likewise switch to issuing "new-quantity" dosemeters on a given date. But they will be obliged, for a period, to process both old and new types. Running "old" and "new" systems in parallel – whether for instruments or passive dosemeters – is inefficient. It will bring added running costs and, importantly, an increased risk of errors. (Note – these added running costs are in addition to the investment costs of adaptation.) Therefore the phasing period should be short.

International standards

A wide range of standards will need thorough revision. Amongst the areas affected are metrology for dosimetry laboratories, type testing and performance, and practice guides and recommendations. As indicated above, some – but not all – costs can be defrayed by merging the process of updating to the new quantities with the normal routine review.

Calibration Labs: Changed practices

Calibration laboratories will need to adapt their procedures and practices. However, because of the need to continue using, for photons, the present arrangement of ensuring charged particle equilibrium, the changes will mainly be around the instrumentation and software.

Reduced Doses at Medical/ Diagnostic X-ray Energies

As indicated above, the new operational quantities remove the existing over-estimation in these medical exposure situations. Measured doses will fall. Stakeholders need to recognise, however, that the "real" doses to individuals – i.e. those represented by the *protection* quantities – will not change. All that is happening is that our estimates of those doses will improve. Therefore, there is no justification for radiation protection measures, such as local rules, automatic controls or shielding, to be relaxed.

Equally, care will be needed in future interpretations of collective doses. Because the new operational quantities will result in lower recorded doses, it could appear that the detriment per unit dose is higher. This is not the case, and it should not lead to a tightening of dose limits.

Over this energy range, adopting the new quantities will not see a commensurate reduction in eye lens doses. It is currently inadvisable to try to control eye lens dose by controlling "whole body" dose as measured on a trunk dosemeter; but adopting the new quantities will make this approach even less justifiable.

Higher Energies

As indicated above, the new quantities allow for consistent dosimetry for higher energies than before, and for a wider range of radiation types. This is of particular use for particle accelerator environments. For aircrew, the new quantities are of limited use, because the widely-used dose calculation routines go directly to the protection quantity, effective dose.

Recommendations

We support ICRU's view that adopting the new quantities should be phased over a timescale of tens of years. This will allow for mature consideration of the many complex issues. It will also allow for the parallel development of new recommendations from ICRP to be taken into account.

Nevertheless, stakeholders should begin evaluating and planning now. In particular, they should look closely at the cost and resource implications, especially around the development of new or modified devices.

Summary

Prepared by Dr. Pawel Olko

on behalf of the

Working Party "Research Implications on Health and Safety Standards" (WP RIHSS) of the Group of Experts referred to in Article 31 of the Euratom Treaty[9]

1. Introduction

This chapter provides the rationale of EU Scientific Seminars, summarises the individual presentations, and the roundtable discussion on policy implications and research needs of this year's Scientific Seminar on *Advances/Innovations in individual dosimetry*. It takes into account the discussions that took place during the seminar, although it is not intended to report in an exhaustive manner all the opinions that were expressed. These proceedings have been submitted for comments to the lecturers and round-table participants, as far as their contributions were concerned.

2. The Article 31 Group of Experts and the rationale of the scientific seminars

The Article 31 Group of Experts is a group of independent scientific experts referred to in Article 31 of the Euratom Treaty, which assists the European Commission in the preparation of the Euratom Basic Safety Standards for the protection of the health of workers and members of the public against the dangers arising from ionising radiation. This Group of Experts has to give priority to protection of health, to safety and to development of the best available operational radiation protection. To this end, the Group of Experts is committed to proactively scanning new or emerging issues in science and technology, and ongoing developments in the area of radiation protection and informing the European Commission on potential policy implications.

In this context, a Scientific Seminar is devoted every year to emerging issues in Radiation Protection – generally addressing new research findings with potential policy and/or regulatory implications. Following suggestions from the Working Party Research

[9] The Scientific Seminar was chaired by I. Prlić. P. Olko was acting as rapporteur. In addition, the following members of the Working Party on Research Implications on Health and Safety Standards of the Article 31 Group of Experts contributed to the preparation of this overview, L. Lebaron-Jacobs, F. Bochicchio, A. Dumitrescu. They were assisted by F. Tzika and S. Mundigl from the European Commission.

Implications on Health and Safety Standards (WP RIHSS), the Article 31 Group of Experts selects the topic of the seminar. After selection of the topic and approval of the programme by the Article 31 Group of Experts, the WP RIHSS deals with the preparation and the follow up of the seminar. Leading scientists are invited to present the status of scientific knowledge in the selected topic. Additional experts, identified by members of the Article 31 Group of Experts from their own country, take part in the seminars and act as peer reviewers. The Commission usually convenes these seminars in conjunction with a meeting of the Article 31 Group of Experts to allow the Group to discuss potential implications of the presented scientific results. Due to the developments with the covid19 pandemic and resulting restrictions as regards physical meetings, this year's Scientific Seminar took place online. Based on the outcome of the Scientific Seminar, the Article 31 Group of Experts may recommend research, regulatory or legislative initiatives. The Experts' conclusions are valuable input to the setting up of the European Commission's radiation protection programme, and to the process of reviewing and potentially revising European radiation protection legislation.

3. Key highlights of the presentations at the Scientific Seminar on Advances/Innovations in individual dosimetry

Ivica Prlić – Objectives of the seminar and introduction to the topic

The objectives of the seminar were twofold. Firstly, the progress in the new techniques opens the possibilities for improving dosimetry and reducing the radiation risk. It concerns new methods in individual monitoring, instruments for pulsed radiation, computational dosimetry and challenges of space dosimetry. Secondly, the new ICRU/ICRP 95 recommendations on new operational quantities provoked many questions on the possible regulatory consequences.

Invited speakers represented several key institutions and organizations active in the field of dosimetry, including International Commission of Radiological Protection ICRP and European Radiation Dosimetry Group EURADOS.

Filip Vanhavere - New dosimetry techniques – an overview (Including eye-lens dosimetry)

Individual monitoring of radiation workers is performed to verify compliance with the dose limits but also to help in optimization of radiation exposure. Traditionally, assessment of individual dose from external radiation is based on readings of personal dosimeters, almost exclusively passive dosemeters. Nowadays, the popularity of Active Personal Dosemeters (APD) is rapidly growing particularly in nuclear industry. For the future, futuristic computational dosimetry techniques combined with on line systems are under investigation for their use in individual monitoring.

Personal passive dosimetry systems are evolving relatively slowly and their basic principles of operation remained unchanged for more than 50 years. The personal dosemeter is worn on the body and gives information about the dose level at the point of exposure. A passive dosemeter integrates the dose over the period of some weeks or months but the result of the measurement is available only after returning it to the dosimetry service.

Nowadays the quality of individual monitoring in Europe has greatly improved. This is mainly due to better energy and angular response of personal dosemeters and, partly due to of introduction of the multi-element dosemeters with advanced computational algorithms. Dosimetry services become larger; most of them undergo accreditation or approval, which in consequence leads to better Quality Control. An interesting development is offered by the INSTADOSE dosemeters, a hybrid combination of passive and active dosemeter.

This progress can be clearly observed in the results of intercomparisons of personal dosemeters, regularly organized by European Radiation Dosimetry Group, EURADOS. The results of these intercomparisons clearly demonstrate very good performance of most of dosimetry services.

Despite all improvements uncertainties in individual dosimetry remain quite considerable as compared e.g. to radiation therapy, where the doses to the patient must be known with the accuracy of a few percent. This is partly due to the nature of the distributed, multidirectional radiation fields but also due to imperfections of energy response in mixed radiation fields. Particularly challenging remain neutron dosimetry and dosimetry of low energy β-rays.

Active personal dosemeters (APD), despite the higher cost, are widely used in some areas of radiation protection, mainly in the nuclear industry. A big advantage of APDs is an immediate readout and alarm waken up in a high-dose rate area. On the other hand, APDs still require periodic calibrations in an approved calibration laboratory in order to operate as a legal dosimetry system. APDs present some limitations for dosimetry in low energy X-rays and pulsed- radiation fields.

The ICRP recommendations from 2011 to decrease the dose limits for eye-lens from 150 mSv to 20 mSv raised the interest for eye lens dosimetry. EURADOS intercomparisons have demonstrated that most of the **eye lens dosemeters,** based mainly on LiF thermoluminescent detectors, perform well in reference radiation fields. However, practical use of eye lens dosemeters is still not convenient because of wearing protective glasses. Therefore, although the measurement capabilities are available for eye lens dosimetry, more practical guidance and solutions are needed to come to proper monitoring of the eye lens doses.

A **futuristic approach to computation dosimetry** was proposed in the EC funded project Personal On-line DosImetry Using computational Methods (PODIUM). The idea was to calculate the effective dose of a radiation worker by tracing his/her positions and movements against the existing radiation fields. Knowing radiation sources, dimensions of the worker and the topology of the exposure one can calculate dose distributions in organs and tissues. The approach was tested for two neutrons fields and for interventional radiology setups resulting in a good agreement with the measured values. The PODIUM project was just the first step towards the novel dosimetry and its outcomes can assist in overcoming problems associated with the use of point dosemeters.

The future of individual dosimetry seems to rely on developments in the field of APD dosemeters and advanced calculations. However, the use of passive dosemeters will certainly be continued, as they present the most reliable source of dosimetry data.

Werner Rühm - Aircrew and space crew dosimetry

It is not widely known that the **aircrew** of commercial aircrafts are one of the occupational groups most exposed to ionizing radiation. The International Commission on Radiological Protection (ICRP), in their reports from 1991 and 2007, recommended that exposure to natural sources be included as a part of the occupational exposure. The EU Directive 96/29 EURATOM obligated the EU Member States to transpose the protection of aircrew into national law.

The key tools for aircrew dosimetry are dedicated computer codes. These codes calculate the effective dose rate as a function of flight altitude, geomagnetic latitude and longitude, and phase of solar cycle, combined with flight profiles. Aircrew dosimetry is nowadays routinely performed by some verified codes, such as EPCARD and others. In Germany and for 2018, the calculated doses have been reported to the national dose registry for about 42,000 aircrew members. In 2018, the mean annual effective dose of aircrew members in Germany was about 2 mSv.

EURADOS published in 2012 results of an intercomparison performed for 11 codes and 23 different flight routes, including the northern and southern hemisphere. The highest median route dose of 95 μSv was obtained for the flight from Singapore to Newark, US. The overall agreement between the codes was better than ±20 % from the median which was considered as a very good result.

This intercomparison took into account exposure to Galactic Cosmic Rays, modified by the solar cycle. The question arose to what extend the codes are also able to calculate route dose in case of solar particle events (SPEs) due to large eruptions on the Sun leading to Ground Level Enhancements (GLEs). Two SPEs were studied for three different flight routes across the Atlantic, the North Pole and the southern hemisphere. The results obtained for the GLE69 showed significant differences by ±90 % from the median. The conclusion of the study was that it is needed to develop "a traceable method to identify and handle the solar proton characteristics related to GLEs" and to verify it experimentally.

Research on **space crew dosimetry** was intensified with the growing human dreams to travel to Mars. It is assumed that during an entire Mars mission lasting up to three years radiation exposure can possibly exceed 600 mSv. In 2013, ICRP published a report on radiation exposure of astronauts in space. The main problem of space dosimetry is the complicated radiation field which includes a variety of particles resulting in difficulties in assessing the relevant Quality Factors to account for risk due to various biological effects.

Historically, the risk in radiation protection was related to the probability of death due to radiation-induced cancer. In 2018, ICRP was asked by the International Systems Maturation TEAM (ISMT-Radiation) including space agencies operating the International Space Station to assess also the role of other radiation effects e.g. on the central nervous system, circulatory system, eye-lens etc. Additionally, various risk metrics will be examined that can be used to assess radiation-related health risks and communicate them to astronauts. The report is currently under preparation.

Up to recently, NASA activities have focused on low Earth orbit (LEO), with the exception of the Apollo missions to Moon. NASA's current approach is to limit the probability of cancer death due to radiation exposure during the space mission to 3 %. Currently, NASA is working to revise this standard due to the planed Moon and Mars missions. An ethical issue is the different risk for cancer death for males and females. The new standard will increase the current permissible exposure for female astronauts from 180 mSv to 600 mSv. Since the mission to Mars may lead to higher doses, an individual risk assessment and a *revised risk communication system* to the astronaut is recommended.

Marco Caresana - Dosimetry in pulsed fields and mixed fields (including radiation protection of personnel in proton therapy facilities)

Dosimetry in pulsed (burst) radiation fields has recently arose to an important issue. It came out that radiation doses from high-energy accelerators measured with several types of active dosemeters (monitors) might be underestimated. This is because many accelerators, including medical linacs, produce bunches of particles in time of some μs, followed by a long time of beam off. The laser-generated beams can produce radiation bursts in extremely short time in fs range.

At these high intensities, the compensation of the dead time in pulse measuring devices such as REM counter might not work properly. This happens when the radiation burst is much shorter than the pulse time resolution of the counter.

The stray radiation maintains the same time structure as the initial burst, particularly for photons. For neutrons, the length of the burst can be extended by their thermalization and drift. The arrival of thermal neutrons to the counter is stretched in time and can be described by the exponential decay curve with a characteristic decay time, τ. For REM counters with a dozen of cm moderator layer τ is of about 100 μs. The effect of Thermalization and Drift Time, TDT, partly mitigates the problem of too short pulses. It is worth noting that the low intensity of radiation does not reduce the problem.

One of the solutions is offered by the LUPIN REM counter (**L**ong interval, **U**ltra wide dynamic, **PI**le-up free **N**eutron survey meter). Instead of the classical electronic chain, the output of a proportional counter is logarithmically amplified and digitally converted. The current is digitally integrated over time exceeding 4-5 times the τ. It allows to pick up the entire charge generated by the radiation burst. From the total charge, the number of neutron interactions in the counter is derived. With this technique, the dead time of the counter is reduced by at least two orders of magnitude.

The advantage of the system was demonstrated during the experimental activities performed by the EURADOS Working Group 11 "High energy radiation fields". In 2012, measurements were performed using different types of active neutron dosimetry systems at the 68 MeV proton cyclotron at Helmholtz Zentrum (Berlin). It was demonstrated that standard REM counters are losing linearity of dose response at doses per burst from 1 nSv to 10 nSv, whereas LUPIN maintained linearity up to about 500 nSv. The capability of the system to measure the pulsed-fields is defined by the half response burst dose, D_{half}, which causes the instrument to underestimate the dose by a factor two. The higher D_{half} the better the instrument performance in pulsed fields. For example, the popular Studsvik 2202 D REM meter has D_{half}= 27 nSv and LUPIN with BF3 counter 1808 nSv.

The measurements performed at the Maastro Proton Therapy Centre, equipped with Mevion SC-250 synchrocyclotron, confirmed the high performance of the LUPIN system. The proton beam is delivered in pulses 10 μs in duration at a maximum repetition rate of 750 Hz. Measurement of scattered neutron fields demonstrated that the response of LUPIN was by a factor of 3 to 10 higher as compared to other REM counters. The results could be a surprise and some results on neutron doses around synchrocyclotron facilities could be underestimated.

To reduce this risk, it is postulated to develop a metrological grade facility for instrument calibration is pulsed neutron fields. At present, investigators and manufacturers have no possibility to verify their instruments or prototypes in metrologically traceable pulsed neutron fields.

Hans Rabus - Computational dosimetry and use of artificial intelligence (AI)

In modern dosimetry, computational codes are becoming an essential and integral part of the radiation protection system. The growing computational power of modern computers facilitates the wide use of Monte Carlo (MC) transport codes, which are effectively used for supporting dosimetry measurements. The fast development of machine learning, which is encountered nowadays, is expected to have a significant impact also on computational dosimetry.

Monte Carlo radiation transport simulations are widely employed in a variety of dosimetry issues. It is nowadays obligatory to deploy codes such as MCNP, FLUKA, GEANT or PENELOPE when designing new detectors and dosemeters. In medicine, radiation transport calculations are already considered as a standard for assessment of the patient dose, in particular in radiotherapy and medical imaging. As a result, these simulation tools are being used by an increasing number of researchers, and more and more papers are appearing in the literature in which different studies on similar problems largely report divergent results.

Therefore Working Group 6 "Computational Dosimetry" of EURADOS periodically organizes exercises (intercomparisons) and training courses to harmonize the use of the computational codes in Europe. In the last two years, several papers were published on results of common exercises on the use of ICRP computational phantoms, unfolding neutron spectra from Bonner sphere spectrometry, microdosimetry of internal emitters and the dose enhancement by gold nanoparticles. The exercises demonstrated that for some problems the values calculated by participants can differ by an order of magnitude from a reference solution. This was the case for the nanoparticle calculations, for the ICRP reference phantom exercises and, within these, particularly for determination of the dose to bone marrow. The exercises enabled participants to verify their computational tools and better understand the problem.

Despite the increasing speed of modern computers, the reduction of computing time and uncertainties remain amongst the main issues in MC calculations. Several techniques are employed to reduce the CPU time such as neglecting processes of minor importance, using cut-offs for terminating particles history, or partly applying analytical functions. A significant increase of the CPU power enabled parallelization of calculations on computer graphics computational units or in cloud computing.

The next step in increasing capabilities of computational dosimetry is expected to be based on the introduction of methods of Artificial Intelligence (AI), and in particular Machine Learning (ML). In ML, neural networks are used that consist of the so-called neurons i.e. functions which are interconnected with other neurons using weighting factors. Before application of neural networks, an initial training of the network is necessary on a large training data set. After the training, the network is ready to solve similar problems. Typically, ML is applied for regression of data or classification of data.

The most commonly used networks architecture in the field of radiation dosimetry are Convolutional Neural Networks (CNNs) and Generative Adversarial Networks (GANs). CNNs are used to replace or support MC calculations by a faster trained neural network. In this approach, MC simulations are generating first the training data and the validation data. So far, this approach has been used in molecular radiotherapy to assess dose distributions from PET/CT images, and in external radiotherapy to calculate the 3D dose distribution from the 2D fluence map. However, still the predictions' uncertainties of the order of 10 % are too high for the requirements of radiotherapy.

An interesting application of ML is a quick analysis of results of radiobiological cell experiments. Radiation-induced foci indicating DNA damage repair can be quickly identified and classified, especially by taking into account more criteria than used in the classical analysis. This can be useful e.g. for identification of foci induced by radiation of different qualities.

The introduction of AI methods in computational dosimetry requires overcoming several challenges. One of them is the development of the standardized performance metrics with quantitative criteria enabling automatic assessment of data quality. Another challenge is the availability of high quality data sets for training, validation, and testing. These data can be generated e.g. by MC calculations but the quality of the data must be verified. The broader application of AI methods in radiation dosimetry is still ahead of us.

4. Summary of the roundtable discussion: policy implications and research needs

Thomas Otto – Roundtable presentation: ICRU/ICRP report on the new operational quantities in radiation protection

ICRU 95 Report on Operational Quantities for External Radiation Exposure has created many consequences for radiation protection. They were discussed by two top experts in dosimetry: Thomas Otto, a member of the ICRU Report Committee leading to Report 95 and Phil Gilvin, a long term chair of the EURADOS Working Group on Individual Dosimetry.

The main key messages of the new report were presented by Thomas Otto and include the following:

1) Existing operational quantities for external exposure based on the ICRU sphere are no more recommended for individual monitoring. For low energy photons they significantly overestimate the effective dose E, and significant over- or underestimate E at very high energies.

2) New operational quantities are proposed, based on the same radiation weighting factors and anthropomorphic numerical phantoms, which are applied for calculation of effective dose. The report offers full set of conversion coefficients needed for calculation of those quantities.

3) The new quantities will led to reduction to about 85 % of H^* and H_p for photons, increasing by a factor of 2 the value for electrons, reducing by a factor of 2 the value for backscattered photons in interventional radiology.

4) Photon dosemeters for ambient dosimetry can be recalibrated for the new quantity H^*. Personal dosemeters will need new algorithms or need to be redesigned to compensate the overresponse at low energies.

In conclusion, the introducing the new operational quantities should improve the approximation of effective dose, E.

Phil Gilvin – Roundtable presentation: Impacts of the ICRU/ICRP report relevant to dosimetry

Dr Phil Gilvin presented the impact of the new ICRU recommendations relevant to dosimetry, in particular individual dosimetry. There are two major benefits of the new quantities namely:

- they are defined for a wider range of radiation types and broader energy range,
- they correct the overestimation for photon energies below 80 keV.

Regarding the practical consequences of the new quantities the existing personal dosemeters will need a range of adaptations. The less expensive would be the recalibration, using different reference radiations or/and adaptation of dose calculation algorithm. However these changes would not likely be effective, especially for simpler, two element dosemeters. The adaptations for the new regulations will be costly, especially when new types of dosemeters have to be used.

Some impact for the uncertainty of measurements with personal dosemeters arises from the fact that two sets of conversion coefficients were published: for so called full-transport and the Charged Particle Equilibrium conditions. To account for that, calibration laboratories need to adopt their procedures but the changes will be probably limited.

The change of the operational quantities for low-energy photons will reduce recorded doses but this fact should not lead to reduction of protection standards.

The adoption and implementation of the new quantities should be phased over a timescale of tens of years, but the stakeholders should start the preparation already now.

Roundtable discussion: Filip Vanhavere, Werner Rühm, Marco Caresana, Hans Rabus, Thomas Otto, Phil Gilvin, Stefan Mundigl, Ivica Prlić (Moderator)

The round table discussion concentrated on the impact of the proposed operational quantities on legislation and practical radiation protection.

Stefan Mundigl recalled the main objectives of the seminar from the Commission's point of view. The latest European Basic Safety Standard Directive (BSS) was published in 2013 and recently transposed into Member States' regulations. The main question, which arises, is related to what will be the impact of the new ICRU operational quantities on the next generation of Basic Safety Standards. This is also related to the ongoing discussion in ICRP on the revision of the system of radiological protection and the potential broadening of the concept of detriment due to radiation exposure. Not only cancer death but also some additional metrics for risk assessment are currently under review e.g. circulatory diseases caused by radiation exposure. The need for research for the implementation of the new ICRU recommendations was noted.

Thomas Otto explained that the different size of humans should not have a major impact on uncertainties of assessment of effective dose using new operational quantities. He also noted that the introduction of the new quantities is not expected to have an impact on the results of dedicated eye lens dosemeters.

An expert pointed out that at the moment we are unable to predict all consequences of introducing the new operational quantities. The highest exposure is currently observed in medicine, in particular in interventional radiology. New quantities are expected to reduce the estimate of the eye lens even by a factor of two but the risk of the lens opacities should remain unchanged.

Marco Caresana argued that for adopting neutron REM counters to the new quantities the change of the calibration factors would be probably sufficient. He formulated a very interesting proposal to use in the newly organized dosimetry intercomparisons, both old and new quantities. It will give sufficient time for dosimetry services to verify the performance of their dosemeters and to be prepared for the future changes.

Werner Rühm underlined that the report 95 is a joint ICRU/ICRP publication and, therefore, also expresses the position of ICRP. For the process of implementation of the new quantities, an additional ICRP report is not needed. Werner Rühm also postulated that, in the future, more analysis should be performed before any change of the new operational quantities is proposed.

Phil Gilvin commented that the formulation of the new quantities should not have a significant impact for the future Basic Safety Standards, in particular for dose limits. Practically, in all cases the old quantities will be just replaced by the new ones.

Filip Vanhavere and **Hans Rabus** stressed again the growing role of computational dosimetry. Application of dedicated codes is already legally accepted in radiation protection of aircrew and there are no major contraindications to apply computational codes also in other branches of individual monitoring. These possibilities should be considered in future regulations.

Conclusions[10]

Based on the presentations and the discussions during the Scientific Seminar, the experts of the Working Party RIHSS identified the following important issues:

1) Despite all improvements, uncertainties in individual dosimetry remain quite considerable due to the nature of the scattered and, multidirectional radiation fields, but also due to the energy response of dosemeters in mixed radiation fields. Therefore, there is still a need to improve energy and angular response of personal dosemeters. Particularly challenging remain neutron dosimetry and dosimetry of low energy β-rays, both for passive and active dosemeters. Moreover, use of eye lens dosemeters is complicated when protective glasses are used. More practical guidance and solutions

[10] These conclusions were prepared by: P. Olko, L. Lebaron-Jacobs, F. Bochicchio, A. Dumitrescu, I. Prlić and E. Carinou. They were assisted by F. Tzika and S. Mundigl from the European Commission.

are needed in order to make the dedicated eye personal dosemeters broadly accepted in hospitals.

2) Active dosimetry around high-energy accelerators is challenging due to the pulsed structure of radiation fields. High intensity of the short pulses makes the compensation of the dead time of the signal in the neutron REM counters ineffective. As a consequence the measured doses are underestimated. This fact is not well known within the radiation protection community, not even for experts. Therefore, for pulsed-radiation fields dedicated REM counters should be applied with a special signal processing. It should be considered to develop metrologically traceable facilities for instrument calibration in pulsed radiation, particularly in neutron fields. It would help both manufacturers and users to verify the performance of their instruments.

3) Computational dosimetry became an integral part of the radiation protection system. In particular, Monte Carlo radiation transport calculations are becoming a golden standard in dosimetry. However, the results of intercomparisons performed by EURADOS demonstrated a significant spread of results, even when calculations were performed using the same codes. Therefore, the use of computational codes in radiation protection should be accompanied by a properly developed Quality Assurance system.

   Several computational codes are successfully used in the assessment of individual doses in aircrew dosimetry. Fast development of the computational methods opens possibilities to assess radiation doses by registration of the movement of exposed person in irradiation field and fast (on-line) calculation of exposure. This method may lead to better estimation of effective dose than from the one based on the readout of a point personal dosemeter located on the trunk. This method of individual dose assessment should be foreseen in future regulations.

   Machine Learning (ML) is now being introduced to dosimetry, in particular for de-noising measured signals and for direct dose estimation. The major challenge of the method is the availability of the relevant databases for training of the ML systems. In addition standardized performance metrics with quantitative criteria enabling automatic assessment of data quality are required. More research is needed to overcome these difficulties.

4) Recommendations of the ICRU/ICRP 95 Report on Operational Quantities for External Radiation Exposure are expected to have an important impact on several aspects of individual monitoring. The quantities are defined for a wider range of radiation types and broader energy range. They also correct the overestimation of effective dose for photons below 80 keV. The adoption and implementation of the new quantities should be phased over a timescale of tens of years, but the stakeholders should start the preparation already now. The European Commission should support this process by funding research projects to implement the recommendations into practice. Such projects may include organisation of dosimetry intercomparisons using both old and new dosimetry quantities.

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct information centres. You can find the address of the centre nearest you at: https://europa.eu/european-union/contact_en

On the phone or by email

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

– by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
– at the following standard number: +32 22999696 or
– by email via: https://europa.eu/european-union/contact_en

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website at: https://europa.eu/european-union/index_en

EU publications

You can download or order free and priced EU publications at: https://publications.europa.eu/en/publications. Multiple copies of free publications may be obtained by contacting Europe Direct or your local information centre (see https://europa.eu/european-union/contact_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex at: https://eur-lex.europa.eu

Open data from the EU

The EU Open Data Portal (https://data.europa.eu/euodp/en/home) provides access to datasets from the EU. Data can be downloaded and reused for free, for both commercial and non-commercial purposes.

Publications Office
of the European Union