INTERNATIONAL SYMPOSIUM ON STANDARDS, APPLICATIONS AND QUALITY ASSURANCE IN MEDICAL RADIATION DOSIMETRY (IDOS 2019): HIGHLIGHTS OF AN IAEA MEETING

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Abstract— **The IAEA in cooperation with several professional societies and international organizations, organized the International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS 2019) in Vienna on 18 to 21 June 2019. The major goal of IDOS 2019 was to provide a forum where advances in radiation dosimetry, at standards laboratories and hospitals, were reviewed and discussed. The Symposium also facilitated interactions between radiation metrologists, medical physicists, safety specialists and researchers in radiation dosimetry, and participation from all income settings was encouraged. The Symposium included topics related to dosimetry standards, medical dosimetry and radiation protection dosimetry with a specific focus on areas where research and development is needed. Very few international meetings facilitate interaction between radiation metrologists, clinical medical physicists and scientists engaged in the development of new standards, computational dosimetry, the traceability chain, codes of practices and cross-cutting research and in so doing, encourage collaborative opportunities in these fields. Participants submitted research contributions, which were reviewed by a scientific committee, and 110 talks and 84 posters were presented. The IDOS 2019 was attended by 424 participants from 77 Member States, including 54 observers.**

Keywords— **radiation dosimetry, dosimetry standards, primary standards, secondary standards, detectors, dosimetry audits, calorimeters.**

Introduction

Accurate measurements in radiation dosimetry are vital in a wide range of medical and industrial applications where the results are critical in reaching decisions relating to the health and safety of patients, radiation workers and members of the public. The development of primary standards followed by their dissemination to end-users, usually achieved through Secondary Standards Dosimetry Laboratories (SSDLS), ensures traceability of measurements to the international system of units (SI) [1, 2]. Dosimetry codes of practice (CoPs) are used jointly with the dosimetry standards, at SSDLs and clinics, to ensure implementation of accurate radiation dosimetry at the national level.

Due to its role in supporting the development of radiation dosimetry worldwide, the IAEA is well positioned to convene international meetings focused on this topic. Indeed, the IAEA has been supporting the development of radiation dosimetry for more than 50 years. During the sixties and seventies, IAEA support focused on the establishment of traceability of measurements and dosimetry audits to improve accuracy in radiotherapy dosimetry. It cooperated with the WHO (PAHO in Latin America) to launch the IAEA/WHO postal dose audits for radiotherapy dosimetry in 1969 [3], and to setup the IAEA/WHO Network of SSDLs in 1976 [4]. The IAEA support gradually evolved to include the development of internationally harmonized dosimetry CoPs in radiotherapy [5, 6], X-ray diagnostic radiology [7], and measurement guidelines for radioactivity measurement in nuclear medicine [8]. To support implementation of dosimetry CoPs and good practice in hospitals, the IAEA has also developed numerous guidelines in medical physics (such as treatment planning, in-vivo dosimetry) as well as education and training material.

The previous IAEA meeting on standards, applications and quality assurance dosimetry was held in Vienna in 2010. Since that time, major developments have resulted in changes in medical radiation dosimetry. The IAEA organized the International Symposium on Standards, Applications and Quality Assurance in Medical Radiation Dosimetry (IDOS 2019) in Vienna on 18-21 June 2019 [9]. The IDOS 2019 was organized in cooperation with several professional societies and international organizations. Participants submitted research contributions, which were reviewed by a scientific committee and presented during IDOS 2019. A total of 424 participants from 77 Member States, including 54 observers, attended IDOS 2019. In addition to scientific sessions and panel discussions, the IDOS 2019 programme included educational courses and a technical exhibition from 21 manufacturers of radiation dosimetry and calibration equipment, irradiators, phantoms and dosimetry software. The major goal of IDOS 2019 was to provide a forum where advances in radiation dosimetry at standards laboratories and hospitals were reviewed and discussed. There are very few other

international meetings where radiation metrologists, clinical medical physicists and scientists engaged in dosimetry, can share developments on new standards, computational dosimetry, the traceability chain and codes of practices, and discuss cross-cutting research and collaboration opportunities in these fields.

VI. International framework for radiation dosimetry

The international framework for radiation dosimetry was presented, highlighting the background and the important roles of the International Bureau of Weights and Measures (BIPM), Primary Standards Dosimetry Laboratories (PSDLs), SSDLs and the International Committee for Weights and Measures - Mutual Recognition Arrangement (CIPM MRA) [2]. The background and functions of the international Consultative Committee for Ionizing Radiation (CCRI) [10] was also presented, stressing the importance of working collaboratively to support each other internationally in terms of the access and use of radiation sources for metrology. Through the CCRI, a review of the recommendations on key data was performed and published in the ICRU Report No. 90 [11] and an international consensus was achieved on the practical implementation of the changes in dosimetry standards worldwide [12].

Worldwide, there are only about twenty countries with PSDLs involved in radiation dosimetry. These PSDLS cannot meet the needs of all end-users for the calibration of their radiation dosimeters. In this context, the importance of the dissemination of standards to the end users through the IAEA/WHO SSDL Network was emphasized [13]. The IAEA/WHO SSDL Network is supported by the BIPM and several PSDLS to ensure that the SI is disseminated as widely as possible. The IAEA dosimetry laboratory is the central laboratory of the Network with calibration and measurements capabilities that have been reviewed by all regional metrology organizations. The quality management system has been approved by the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB). Traceable standards are disseminated to SSDLs that have no access to BIPM and PSDLS. The IAEA has setup comparison programmes with SSDLs to help verify that the services provided by the SSDL members follow internationally accepted metrological standards [14]. The IAEA/WHO SSDL offers calibrations for radiotherapy (external beam and brachytherapy), radiology and radiation protection level instruments and issues approximately 100 certificates per year. About 20 comparisons are conducted annually. The IAEA dosimetry laboratory is also involved in capacity building and increasing the number of SSDLs worldwide.

VII. Radiation dosimetry standards

2.1.Developments at primary standards dosimetry laboratories

The BIPM and National Metrology Institutes (NMIs) are continuing to develop and improve their dosimetry standards. The National Physical Laboratory (NPL) reported on the development of an absorbed dose to water primary standard for radiopharmaceutical therapy [15]. This allows the determination of absorbed dose based on direct measurements rather than using tabulated nuclear data. The standard is based on a conventional extrapolation ionization chamber. The NPL also reported that a graphite calorimeter has been developed for use in clinical proton beams [16]. The doses obtained using the graphite calorimeter are consistent, within the uncertainties, when compared to the doses derived using TRS 398 [6], but with improved uncertainties.

The National Institute of Standards and Technology (NIST) developed a thick brass wall chamber to directly realize air kerma in photon fields from a megavoltage x-ray-based inspection system with energies ranging between 1 MeV and 6 MeV [17].

Air attenuation corrections for free air chambers are currently based on measurements, due to the large uncertainties historically associated with photon cross-sections and the estimation of the x-ray spectrum. Based on work at the National Research Council (NRC) [18], these calculated values are in closer agreement with the measured values if the renormalized photoelectric cross-sections for low-energy x-rays are used, as recommended by the ICRU Report No. 90 [19]. The result of this research can help establish confidence limits for Monte Carlo (MC) calculated air attenuation corrections for free air chambers.

Brazil reported on the results of characterizing Fricke dosimeters, as a primary standard for brachytherapy sources, to determine absorbed dose at the reference distance of 1 cm [20]. The results obtained are promising, demonstrating that Fricke dosimetry shows good potential as a primary standard for HDR ^{192}Ir sources.

2.2.Developments at secondary standards dosimetry laboratories

Primary standards are used by PSDLs to provide calibrations, usually to the SSDLs, which in turn calibrate the reference instruments of users. For x-ray dosimetry, SSDLs have to establish the reference beam qualities used for the calibration of their reference standards at PSDLs. Several SSDLs reported on their work to establish calibration capabilities for x-ray diagnostic radiology, including mammography [21, 22]. The SSDL of Poland presented an analysis of 18 ^{192}Ir air kerma calibration results over 6 years, using a traceable

reference standard well-type ionization chamber (PTW 33004), which had a long-term stability of 0.3% [23]. Calibration of radiation protection instruments is generally performed using ^{241}Am, ^{137}Cs and ^{60}Co sources however, the response at 200 keV is not tested using this approach. However, backscattered Compton photons obtained from the ^{137}Cs source can be used to generate an appropriate field for this purpose [24].

2.3.Computational dosimetry

Confirmation of the mean energy to form an ion pair in dry air (W_{air}) value as published by the ICRU Report No. 90 [11] has been limited to electrons of energies up to 5 MeV. Preliminary data on a proposed aluminum calorimeter, as an alternative to graphite, in order to establish whether W_{air} varies as a function of electron energy, were presented. A consistent result of 33.82 ± 0.27 eV was calculated for clinical electron beams up to 22 MeV [#140]. Monte Carlo simulations of radiation transport are increasingly becoming accepted in the community to derive correction coefficients or to confirm, predict or interrogate experimental findings, however, several mathematical models of Compton scatter exist, for instance. Four theories, each using different approximations, were compared by calculating mass energy absorption coefficients for water and graphite, and major differences between the models were only found at energies at which the photoelectric effect dominates [309]. Preliminary results of the use of computational codes to study ionization quenching in scintillators [244], to develop a prompt gamma ray imaging system for particle beams [73] and to model alanine dosimeters in low energy x-ray beams [266], were also presented. The NPL presented results of calculated conversion and correction factors for a graphite calorimetry primary absorbed dose to water standard for ^{192}Ir high dose rate brachytherapy [104].

III. CODES OF PRACTICE IN RADIOTHERAPY DOSIMETRY

Radiation dosimetry CoPs constitute the final step in the dosimetry chain and are implemented by end-users. In radiotherapy, CoPs are used in conjunction with a reference quality ionization chamber, calibrated by a standards dosimetry laboratory, in order to determine a radiation dose under standard reference conditions. The CoPs TRS-398 [6] and TG-51 [25] are applicable for conventional radiotherapy, but they are not suitable for technologies that can only produce small fields. In some cases, accidents have occurred owing to the use of detectors, methods and procedures that are appropriate for large fields but not for small fields [26].

3.1. Small Field Dosimetry

In 2017, the IAEA and the American Association of Physicists in Medicine (AAPM) jointly published a CoP on the dosimetry of small static fields used in external beam radiotherapy (TRS-483) [27]. The CoP provides guidance for reference beam dosimetry of machine-specific reference fields, as well as relative dosimetry. In 2015, the IAEA initiated a coordinated research project (CRP E2.40.21) to test the implementation of the recommendations given in TRS-483. Investigators from eleven different countries were invited to participate in this initiative. Several different detectors were used and all technologies referred to in TRS-483 were investigated. The results of the group's investigations were presented during IDOS 2019. For equivalent square small field sizes of less than 1 cm, large differences in field output factors were found for most technologies because detectors were used that are not recommended for these small field sizes or no field output correction factors had been published [28]. The uncertainties arising from traceability for absolute dosimetry, machine setup parameters and the period since multileaf calibration on determining output factors for relative dosimetry ranged from (0.5 to 3)% [29]. Investigators also presented output correction factors for solid state detectors and ionization chambers (in different orientations) for which there is a lack of data [30]. Measurements of percentage depth dose in small fields showed that small volume ionization chambers exhibit an effective point of measurement of less than half the radius upstream. In addition, the polarity applied to small volume ion chambers and the type of solid state detector used, giving different results in the near surface region, was also presented [31].

The preliminary results of an IAEA pilot study of a new remote audit methodology for small field photon beams were presented [32]. The audit consisted of irradiating Gafchromic EBT-3 films and radiophotoluminescent glass dosimeters (GD-302M) and comparing the measured dose values to the dosimetry data calculated and provided from the local Treatment Planning System (TPS) that is used clinically. Data from 8 countries and 20 photon beams were analyzed. The results for field sizes greater than or equal to (2 x 2) cm^2 were all within 3% but (1 x 1) cm^2 or 1 cm diameter field sizes showed a much greater spread with many points falling outside this acceptance criterion.

An investigation dealing with the field size limitations of the RefleXion biology-guided radiotherapy (BgRT) system was presented [33]. This BgRT system delivers a 6 MV flattening-filter free (FFF) beam with a field width limit of (2 or 3) cm thus, the largest field size attainable that is the closest to a conventional (10 x 10) cm^2 field size is a (10 x 2) cm^2. Two approaches were presented to overcome this small reference field size challenge. The first approach was to generate a correction factor through MC calculations to account for the differences in field

sizes. The second approach was to follow the TRS-483 formalism but with modifications due to the BgRT system not having a typical machine specific reference field or appropriate tabulated data for beam quality corrections. The two approaches were compared for six different detectors and found to be within 0.3% of each other. Ion chambers with a high atomic number central electrode, need to have a correction applied for perturbation effects.

The implementation of the plan class-specific reference (pcsr)-field concept for dynamic fields as described in the 2008 formalism [34], has proven difficult due to a lack of quantitative guidelines and guidelines. To help bridge this gap in knowledge, a multidimensional feature analysis and clustering analysis of numerous modulated treatments was conducted, aimed at determining if distinct plan clusters may help guide the creation of representative plans. A total of 627 clinical plans were investigated. The findings indicated that there were no intuitive plan clusters for a single technique and that it might be more useful to consider corrections on a class solution basis [35].

3.2.Update of TRS-398

Numerous developments have occurred since TRS-398 [6] was published in 2000, justifying the need for updating this CoP. From the Agency's perspective, few users have requested clarifications on implementing the CoP since its publication but revised scientific data, and advances in machine and detector technologies have been the primary reason necessitating an update. The process to update the TRS-398 began in 2016 and took into account the feedback from end-users, new ion chambers, new radiotherapy technologies, updated data from ICRU Report No. 90 [19], and the lack of $N_{D,w}$ calibrations for dosimetry of kV x-rays. The updated dosimetric data (e.g. beam quality correction (k_Q) values) are still under development, based on the revised ICRU-90 stopping power values for graphite, water and air. For photons, the adopted values are those based on renormalized photoelectric cross sections for all materials. The main planned updates are summarized below [36].

- *High energy photon beams (up to 25 MV)*: In addition to new k_Q data, the main update is the introduction of an additional chamber-dependent correction k_{vol} for the dosimetry of flattening-filter free (FFF) photon beams, to account for the volume averaging effect whenever the beam profile across the detector is not homogeneous. The recommendations are consistent with the TRS-483 (25) code of practice, however, dosimetry for novel technologies that are not in widespread clinical use, e.g. MR-linacs, has not been included.
- *High energy electrons beams (from (3 to 25) MeV)*: No substantial changes have been introduced other than new k_Q data. The procedures for reference electron dosimetry were rationalized, to avoid the use of plastic phantoms and to harmonize the use of intermediate beam qualities for cross calibrations.
- *Kilovoltage x-ray beams*: Considering that a major change in the new ICRU Report No. 90 data is due to cross sections and coefficients for the photoelectric effect, a revision of the dosimetric data available for x-ray beams in TRS-398 was deemed necessary. New values of backscatter coefficients and ratios of mass energy-absorption coefficients for water to air (free-in-air and at 2 cm depth in water) have been calculated for various x-ray beam qualities (in terms of both kV and HVL), field size and focus-surface distance. A large database of these values has been developed that will be accessible through an IAEA web page. For the dosimetry standards, PTB confirmed that absorbed dose to water ($N_{D,w}$) calibrations for low-energy x-rays are based on air-kerma standards (N_K), which are then converted into $N_{D,w}$. In the case of medium-energies, absorbed dose to water standards are available in a few laboratories, however dissemination has been limited and the air kerma-based procedure still remains the most frequently used calibration modality. The TRS-398 CoP update will incorporate both methodologies.
- *Proton and heavier ion beams*: The updated edition of TRS-398 will include guidance and data for the determination of absorbed dose to water for the newer proton and light-ion beam delivery systems available in the clinic i.e. broad-beam delivery systems using scattered or uniformly scanned beams, as well as for pencil beam scanning systems using monoenergetic intensity-modulated scanned beams. Additionally, it has been noted that the two-voltage technique for the recombination correction in ionization chambers can lead to significant errors. The recommended correction procedures account for the beam behavior with respect to recombination, either as a continuous or as a pulsed beam.

– *k_Q value determination*: Owing to advances in simulation techniques, values of k_Q for a large number of ionization chambers have been determined with MC. For some chamber types however, values of k_Q for photon and electron beams have also been obtained experimentally at standards laboratories. The resulting MC and experimental sets of k_Q values for each chamber will be combined statistically to obtain consensus mean values and estimates of their relative standard uncertainty.

3.3.Update of TG-51

An addendum to TG-51 for high energy electrons is being prepared. The update will include new beam quality conversion factors and simplified calibration procedures such as removing the requirement for a measured gradient correction and the possibility of using a cylindrical ionization chamber for all energies [37]. It is expected that these changes will lead to fewer calibration errors being made.

IV. Radiation dosimetry

This section summarizes the highlights of several sessions that addressed topics related to measurement techniques in radiation dosimetry in radiotherapy, nuclear medicine, X-ray diagnostic radiology, radiation protection and experimental radiobiology.

4.1.Dosimetry for Radiotherapy

4.1.1.Out of field dosimetry

The European Radiation Dosimetry Group (EURADOS) presented results to assess out of field dosimetry for typical photon and proton treatment techniques used for pediatric radiotherapy of a brain tumour and treatment of the entire cranio-spinal axis [38]. Pediatric anthropomorphic phantoms (5 and 10-year-old) containing radiophotoluminescent (RPL) and two types of thermoluminescent (TL) dosimeters for x-ray doses, and bubble detectors and Polyallydiglycol carbonate (PADC) detectors for neutron doses, were used. The results show that TL detectors consistently record higher doses than RPL dosimeters and that overall, proton therapy reduces the out of field doses for these pediatric cases.

The results of calculated organ neutron doses from an 18 MV radiotherapy linac, using MC simulations were presented [39]. Detailed models of a female patient, linac and linac bunker were generated. An analysis of the effect of varying key linac components on the calculated neutron component of organ dose was also performed and the flattening filter composition caused the greatest change in neutron dose. The highest neutron doses were calculated to be next to the photon treatment field. This type of MC simulation of neutron dose calculations continues to increase our knowledge of out of field dosimetry for high energy photon beam treatments.

The evaluation of the doses for different organs at risk during Positron Emission Tomography / Computed Tomography (PET/CT) examinations for treatment planning, and kV planar and cone-beam CT (CBCT) image-guidance during head and neck radiotherapy was presented [40]. The average effective dose from PET/CT internal exposure was 4.31 $\pm$ 0.97 mSv in the range 2.19 – 5.89 mSv. From the analysis of 22 patients, the average CT dose index value was 55.80 mGy, the planar imaging delivered effective doses in the range 0.354 – 1.416 mSv and the average number of image guidance procedures during radiotherapy was 7.33 (2 to 10) per patient. This work demonstrated the need to be cognizant of the added radiation doses from imaging.

The efficacy of using Optically Stimulated Luminescence Dosimeters (OSLD) for in vivo out of field dosimetry by measuring entrance and exit doses was investigated [41]. A comparison was made of measurements using OSLDs and Thermo Luminescent Dosimeters (TLD) which were placed near the eyes of 10 head and neck patients. The doses measured with the OSLD were found to differ from the TLD doses, where the TLD were considered to be more accurate. The authors suggested that OSLD might not be the detector of choice for out of field measurements.

4.1.2.Dosimetry in the presence of magnetic fields

Magnetic-Resonance (MR)-linear accelerator (linac) guided radiotherapy allows real time organs-at-risk and target localization during treatment with enhanced soft tissue contrast and no additional radiation dose to the patient, increasing its potential in adaptive treatment strategies [42]. The number of these machines in clinical use is expected to grow over the next few years. Integrated systems with differing field strengths as well as magnetic field orientation (parallel or perpendicular) relative to the treatment beam, are being developed. A key issue regarding dosimetry in the presence of a magnetic field is the “electron return effect” (ERE), which is enhanced at solid/air interfaces. Dosimetric investigations have been made of the buildup effect, and detector type, design, response and orientation. Solid state detectors showed orientation effects of up to 20%. Magnetic field correction factors for Farmer-type chambers have been measured and calculated for different magnetic field strengths and field orientations [43, 44]. The ERE on ion chamber measurements has been studied, showing a general trend of increased signal with greater magnetic field strength, whose magnitude depends on the air cavity size.

The PTB presented the design of a new water calorimeter to be used for measuring the dose in a 6 MV beam from a 0.35 T MR-linac [45]. Special considerations were avoidance of ferro-magnetic materials, physical size (the MR-linac used had a bore diameter aperture of 70 cm), horizontal irradiation geometry and insulation. This device allowed for the direct calibration of various ionization chambers in parallel and perpendicular orientations with standard uncertainties of 0.6%. Further measurements are planned for a different MR-linac beam system. Similarly, a Canadian research team [46] presented the design of a MR-compatible water calorimeter that could be positioned using kV, CBCT or MR imaging. Finite Element Method (FEM) software and MC simulation of heat transfer were used to design the calorimeter. Based on the optimum design, a calorimeter was constructed, and its performance evaluated in a 7 MV beam from a 1.5 T MR-linac. The most difficult aspect of the construction was the thermal shielding needed to isolate any external temperature change influence.

The manufacturing details and use of a new ion chamber-shaped graphite calorimeter intended for use as an absolute clinical dosimeter for high energy photons in the presence of a magnetic field, was presented [47]. Magnetic field correction factors were calculated and measured. Within the uncertainty of the measurements, the graphite calorimeter agreed with the ion chamber measurements. There was more variability in the ion chamber measurements than observed with the calorimeter. Results from the study suggest that the calorimeter can be used in a solid phantom in the presence of a 1.5 T magnetic field without significant detector rotation or orientation corrections, with a combined relative standard uncertainty of 0.8%. Further measurements will be made in different magnetic field strengths and for other clinical dosimetry measurements.

A process to make FEM adjustments to ion chamber simulations was described in order to improve the agreement with dose measurements in the presence of a magnetic field [48]. The adjustment involved semi-empirical modification of the sensitive volume of the ion chamber using the FEM in order to correct for electric field lines that end in the guard as opposed to the collecting electrode. Monte Carlo calculations using EGSnrc and GEANT4 were compared. The deviations between the measurements and the calculations with the FEM modifications were within 1 % for all irradiation conditions [49]. The GEANT4 calculations will be extended to include simulation of the electric field.

The Australian Clinical Dosimetry Service has initiated development of an independent dosimetry audit for MR-linacs [50]. A 6 MV FFF beam was used with a 1 T inline MR-linac [51]. A multi-chamber comparison was performed for three ion chambers, a microdiamond detector, alanine and EBT3 film in solid water and liquid water. All measurements agreed to within 1% after magnetic field corrections were applied to the ion chambers. An end-to-end IMRT audit was also conducted using a commercial anthropomorphic phantom that was modified to enable visualization of the detector position and surface contour on the MRI images.

4.1.3.Protons and beyond

There are currently 73 proton therapy facilities and 11 carbon facilities in operation worldwide [52]. Significant technological developments have taken place for proton and light ion (atomic number < 10) beam generation systems over the past few years. The use of monoenergetic scanning beams is now widely available. This is in contrast with the technology used 20 years ago, when passively scattered proton beams were practically the only option available.

An introduction to the main topics to be included in the upcoming ICRU Report No. 93 was given [53]. The main recommendations in the new ICRU report is to discourage the use of gray (Gy)-relative biological effectiveness (RBE), and to rather include a descriptor to qualify dose. For dose reporting therefore, the absorbed dose, RBE-weighted dose and dose-weighted linear energy transfer (LET) should be recorded. In addition, reference dosimetry should be in accordance with the IAEA TRS-398 update.

A talk indicated that reference dosimetry for scanning proton beams [54] requires that the monitor units (MU) are typically calibrated in terms of number of particles since treatment planning systems calculate the number of protons per spot. This can be derived from the dose-area product (DAP), which can be performed with a cross-calibration of a parallel plate ionization chamber or a large-area ion chamber. For scanning beam calibration in the entrance region, it is important to account for the dose gradient if a Farmer chamber is used and the residual range (Rres) is less than 15 cm. For calibration in the center of a spread-out Bragg peak (SOBP), the beam ripple should be taken into account. While limited data exists, experimental k_Q data was compared to MC calculations and agreed well.

The next presentation showed that for proton beams produced by cyclotrons and synchrotrons, the recombination behaves like a continuous beam. For proton beams produced by a synchrocyclotron, the recombination behaves more like a pulsed beam. Care should be taken when calculating k_{sat} with higher polarizing voltages. Two methods for calibrating monitor chambers in a synchrotron for particle therapy were described [55]. The first method determined absorbed dose to water at a shallow depth in a single energy layer scanned pencil beam using a PTW Roos chamber. For the second method, a single energy static spot was measured using a large-area ion chamber. The results of the two methods were compared over a range of energies and differences of up to 3.2% were observed. The chamber

readings for the large-area ion chamber can be corrected to get agreement within 1%. Either method may be used with a combined standard uncertainty of about 2.6% (1σ), however, there are concerns over the homogeneity in response over the active volume of large area ion chambers [56].

The NPL described a comparison of the measured dose per MU at a water-equivalent depth of 2 cm of 6 user- and 7 reference-ion chambers, that was performed in passively scattered and scanning proton beams in 3 clinics [57]. Ion recombination was compared in a low-energy passive scattered beam using the two-voltage method, which underestimated the recombination. Clinical centers calculated recombination corrections differently, and standardization is recommended. There was agreement within 1.2% in proton beam calibration between the NPL and the clinical proton centers. Additional measurements in composite fields however, showed discrepancies up to 3.1%.

The NPL also described the use of a portable primary standard graphite calorimeter for proton beams (scanned and scattered) [58]. Monte Carlo calculations were performed to determine several correction factors for the graphite calorimeter as a function of energy and beam diameter. The correction for the presence of vacuum gaps was up to 0.8% in small fields, and within 0.1% for large proton fields. The dose averaging correction was within 0.3%. For the proposed primary and secondary standard test volumes, the corrections were found to be less than 0.1%. For the passive beams however, the dose averaging correction was much larger (2.6%).

An analysis of MC calculations was presented using GATE 8.1 and Geant4 to investigate the possibility of using a phantom containing an ionization chamber and alanine detectors for an end-to-end audit methodology for ion beam dosimetry [59]. Correction factors are necessary to account for stopping power ratios and relative effectiveness. Experimental data were compared to MC (GATE) and TPS dose calculations based on an independent MC dose engine. It was indicated that future work will focus on carbon therapy.

The next talk described absorbed dose to water measurements with ion chambers and a water calorimeter that were performed in a carbon ion beam in China [60]. The beam quality correction results obtained with different ionization chambers agree well within the uncertainty of measurement to the values provided in TRS-398.

The “Proton and Beyond” session ended with a talk looking at the effect of the revised key data from the ICRU Report No. 90 on the calculation of beam quality correction factors for the calibration of a carbon beam [61]. The ICRU Report No. 90 does not include stopping power values for several of the light ion fragments that make up part of the carbon therapy beam, and efforts were undertaken to calculate these values as well. The updated beam quality factors agreed better with experimental data for cylindrical chambers, especially where updated ^{60}Co perturbation factors were available. For plane-parallel chambers however, discrepancies up to 2% were found that require further investigation.

4.1.4.Dosimetry audits for new technologies

Dosimetry audits for advanced techniques and new technologies are necessary to assess quality and safety, to reduce delivered dose variability between institutions, to maintain and improve standards, and to support implementation of complex techniques [62]. Levels of audit begin with assessing beam calibration, expand to non-reference beams and assessing the TPS, and then end-to-end QA testing can be used to verify the whole treatment chain. Independent audits have been key to assessing new technology introduced into radiotherapy and they are often mandatory for credentialing to participate in multi-institutional clinical trials. In order to keep pace with the rapid pace of technological changes, new audit methodologies need to be devised and updated continually; however, this may be inefficient and costly if only on-site tools are developed. Prospective risk management strategies, such as Failure Modes and Effects Analysis (FMEA), could be considered which inform the development of dosimetry audits that focus only on the most critical processes. Other strategies could be the transmission of raw data to central repositories for analysis and the development of regional external audit groups with shared resources.

The details of an end-to-end head and neck IMRT audit that was conducted with on-site visits to 20 institutions in Portugal using the IAEA methodology (SHANE phantom) [63] were presented. The visit also included an audit of multi-leaf collimator (MLC) performance and machine calibration, as well as verification of TPS-calculated 2 cm x 2 cm field profiles and small field output factors. The MLC test showed all MLCs to be calibrated to within 0.5 mm at all institutions. All centers passed the output factor verification audit for field sizes greater than 3 cm x 3 cm, and calculated beam profiles were found to differ by up to 2 mm from measurements. Differences between the measured SHANE phantom doses and the TPS dose calculations were all within the 5% criterion for the PTV and 7% for the spinal cord OAR. Similarly, the initial results of a remote end-to-end prostate IMRT audit in Brazil were presented in which the local clinical protocol is applied to an anthropomorphic phantom and the results are centrally analyzed [64]. A phantom was designed and constructed with targets and organs at risk into which TLDs and film were placed. The results from the first 15 institutions irradiating this phantom were presented that showed the percent of institutions meeting acceptance for the planning target volume (PTV) TLD, organs at risk (OAR)

TLD and gamma index % to be 86.7, 66.7, and 80.0 %, respectively.

The National Research Council of Canada (NRC) described efforts to use alanine as a remote dosimeter for the validation of beam output [65]. Alanine has potential as a more accurate and precise dosimeter than other passive dosimeters used for mailed postal audits, including for high dose industrial applications. Comparisons between the NRC and the NPL were performed for absorbed doses of 15 to 1000 Gy. The comparisons of the two alanine systems were within 0.7%, with both laboratories claiming a standard combined uncertainty of within 0.7%.

An end-to-end dosimetry audit for proton therapy describing the use of alanine at five European proton centers [66] was described. A homogeneous plastic phantom and two anthropomorphic phantoms (pelvic and head and neck) have been modified to accommodate ion chambers, alanine and radiochromic EBT3 film. The phantoms were irradiated and the results from the three dosimeters were compared. The ion chamber and alanine results were within 3% of the calculated doses. A similar dosimetry audit methodology is being developed for carbon ion beams.

The IROC Houston QA Center's remote and on-site dosimetry comprehensive audit programme for proton therapy that monitors 42 proton centers [67] was presented. This audit programme includes remote annual monitoring of proton beam outputs using TLDs, performance of on-site dosimetry measurements and use of anthropomorphic phantoms for end-to-end audits. The overall anthropomorphic phantom pass rate is currently at 73%, with the lung phantom producing the lowest pass rate. Improvements in pass rate have been seen with MC TPS algorithms. Thirty-five site visits have been performed at 27 proton centers with the mean number of recommendations being four. Houston IROC has developed a robust audit programme for proton therapy that promotes more consistent and comparable proton treatment, which benefits participation in clinical trials.

The QA credentialing activities for 6 carbon ion facilities (8 different beam lines) in Japan that participate in multi-institutional clinical trials were described [68]. The QA activities include a questionnaire and an on-site peer review process. The site visit includes a dosimetry audit of the beam calibration for each line at two beam energies in a homogenous water phantom. The average discrepancy between measurements and TPS calculations for absorbed dose to water was 0.6% with an uncertainty of 1.4%. The maximum discrepancy was 2.7%.

4.2. Dosimetry for X-ray Diagnostic and Interventional Radiology

4.2.1.Patient dosimetry

There is a clear need for accurate dosimetry in medical exposures, in particular for the optimization process [69]. The European research project, Medical Low Dose Radiation Dose (MEDIRAD) is developing a patient-specific MC simulation with CT scanner-specific parameters in order to produce a voxel to voxel representation of the radiation dose distribution that corresponds to the CT image. This aims to provide accurate patient-specific organ doses from CT examinations. The MEDIRAD project aims also to develop a real-time tracking software for peak radiation skin dose in interventional radiology and to produce a staff radiation dose tracking system based on the physical location of the staff in the X-ray room. The latter, if successful, could potentially eliminate the need for personal dosimeters in the near future.

The scientific community in diagnostic imaging is moving towards personalized CT dosimetry. An interesting study focused on this subject and illustrated a four-step process starting with the actual patient CT scan, followed by the generation of a segmented 3D CT image, and the use of an "equivalent CT source" model in a MC calculation, to produce a 3D dose distribution that estimates the organ doses within 2 min following the patient's CT scan [70]. Semiconductor embedded probes in a CT phantom were used to compare the MC and measured doses, which agreed within the standard uncertainty of (5 to 10%) for three different manufacturer models.

Mammography examinations are very important from the radiation dose perspective because the procedure is routinely performed on healthy women without any clinical problems. Salomon, et. al. investigated the use of semiconductor dosimeters in dosimetry for mammography. Eight such detectors were calibrated at the IAEA for a range of mammography beam qualities [71]. Five dosimeters complied within the ±5 % stated by the IEC for air kerma.

Lau et al described the application of automated volumetric-breast-density measurement software for the MC calculation of mean glandular dose (MGD) and compared their results with those provided on the X-ray console by the manufacturer [72]. The comparison showed that manufacturers' calculations are lower than the MC results and thus underestimate patient's breast dose.

The development of a new breast model that identifies the distribution of glandular tissue within the breast, which is realistically neither uniform nor concentrated in the centre of the compressed breast, was presented [73]. This model is needed for more accurate patient-specific dosimetry.

Fedon et. al. estimated the entrance skin dose arising from angiography for four age-groups of children with heart disease [74]. Patient skin dose was either estimated using Dose-area-product (DAP) measurements and a

conversion factor from the literature or determined using TLD and 4 different phantoms sizes. Comparison of DAP-derived doses with TLD-measured doses indicated that DAP estimated skin doses overestimate patient skin doses

4.2.2.Dosimetry as a tool for optimization and auditing

Tsapaki provided numerous examples of optimization in routine clinical radiology practice, highlighting the usefulness of dose management systems in the speedy evaluation of patient dose. The importance of engaging all staff in the optimization process, even though this may take time and requires patience, was emphasized [75].

The use of 1 mm bismuth shielding placed on the neck, was found to reduce thyroid, eye lens or other organ doses by as much as 60 % during CT of the cervical spine [76]. This was without loss of diagnostic information, although the images were slightly (1%) noisier. An experimental methodology to evaluate and reduce lung and thyroid organ doses in routine pediatric chest CT, using optimized clinical protocols, was presented [77]. Dose savings of 25% for the lung and 13% for the thyroid were achieved with acceptable CT image quality.

4.2.3.Monte Carlo for dosimetry in diagnostic and interventional radiology

Monte Carlo studies are an important component in modern x-ray dosimetry and contribute to reference dosimetry for diagnostic and interventional radiology through, for example the calculation of backscatter factors and mass attenuation coefficients [78]. Such calculations also allow the determination of dose conversion coefficients derived from anatomical phantoms and corrections for phantom material and phantom thickness. Monte Carlo is used in diagnostic radiology to investigate the components of the detection system, to determine physical factors such as the scatter-to-primary ratio and the backscatter ratio, to determine energy spectra such as the backscatter spectra and to estimate absorbed doses related to radiation protection aspects. Monte Carlo can also be used to interrogate the design of x-ray tubes.

4.3. Dosimetry for Nuclear Medicine

There are pros and cons of highly patient specific voxel level internal dosimetry compared with model based calculations that rely on S-values (dose per unit cumulated activity) generated for reference phantoms [79]. The trade-off between accuracy and speed, the available tools and the application should be considered when selecting one over the other. Although voxel-level dosimetry using Monte Carlo radiation transport is generally considered as the most accurate, phantoms used for the S-value calculation have evolved substantially since the mathematical phantoms of the 1960's (e.g. the Fisher-Snyder phantom used for MIRD 11 S-values). Recent S-values, such as those used by the ICRP, are based on voxel phantoms and hybrid phantoms combining the advantages of mathematical and voxel phantoms that are highly realistic and allow for more flexibility. Hence high accuracy can be achieved, even without the computationally demanding Monte Carlo based voxel-level calculation that rely on the patients' own images. When resources for voxel-level dosimetry are not available, the calculation can be made patient specific to some extent by using scale factors that depend on the organ masses specific to that patient. For homogeneous tissue, voxel-level dosimetry using dose point kernel convolution methods, can be in close agreement with Monte Carlo based calculations. When voxel size is large compared with the beta-particle range, dose estimation assuming local energy deposition can be sufficient for beta emitters that do not have associated gamma-rays (e.g. ^{90}Y). The presentation also included a discussion on the emphasis in diagnostic vs. therapeutic dosimetry in nuclear medicine. For diagnostics, the priority is for traceability whereas for therapy, it is on improving the accuracy of dosimetry.

4.3.1.Developments in nuclear medicine dosimetry

Dosimetry models are used to calculate the mean dose absorbed by the cell nucleus from Auger radionuclides in order to investigate the biological implications of subcellular localization of such electron emitters [80]. When there is no subcellular localization of activity, conventional electron dosimetry was sufficient. However, when activity is in the cell nucleus, conventional dosimetry strongly underestimated the absorbed dose.

The specific objectives of the of the Molecular Radiotherapy (MRT) project were described [81]. The MRT Dosimetry project focusses on the metrology needed for clinical implementation of dose estimation in MRT and builds on the previous MetroMRT project where the focus was on providing tools, protocols and guidance. One goal of the MRT Dosimetry project is to provide an open access database of reference images (phantom measurements and MC simulations), to be used as reference data for commissioning and quality control of SPECT/CT quantitative imaging. Other goals include improving accuracy and determining uncertainties associated with the various steps of the dose estimation chain as part of a multi-site dosimetry comparison.

Insight into clinical alpha particle dosimetry was given, highlighting its ultimate goal to link true microscopic 3D dose distributions to biological effect on both tumour and healthy tissues. The current lack of such data for patients is an obstacle for a wider clinical use of alpha-emitting radionuclide therapies [82]. The challenges of planar and SPECT/CT imaging of alpha emitters due to the low-count rates and multiple gamma-

rays was discussed. Images and dosimetry results from their clinical trial on intraperitoneally administered ^{211}At-MX35 F(ab')2 for therapy of disseminated ovarian cancer was presented.

Iso-effective adaptive biological treatment planning in peptide receptor radionuclide therapy could be used to establish personalized prescriptions [83]. Bootstrapping techniques could be used to consider the influence of random error on dose estimations and inter-patient variation of the linear-quadratic (LQ) model adapted to radiopharmaceutical radiotherapy parameters. Their formulation could be also used to compare different therapeutic schemes or therapies with different radiopharmaceuticals or combined radiotherapy schemes.

The parametric optimization of a predictive mathematical model for the final thyroid mass determination, assuming heterogeneity of thyroid gland mass density, was presented [84]. The effect of actual mass density and changes during the treatment on the dose received by a thyroid was considered in contrast to previous models which assumed a constant density of 1 g/cc. On this basis, they optimized the parameters in the mathematical model predicting the smallest deviation between the measured and calculated volume of a Grave's diseased thyroid.

A methodology for patient specific dosimetry that enables the creation of 3D absorbed dose maps for patient specific dosimetry in radiosynovectomy with ^{153}Sm labelled Hydroxyapatite, was described [85]. Instead of assuming a voxel composition of water, 4 different tissue groups based on CT Hounsfield units were defined and tissue-dependent S values were determined. This method allows a qualitative assessment of the treated volume extension and it can be used by the clinical staff as a tool to establish a connection between total absorbed dose and therapeutic effect.

4.3.2.Dosimetry in therapeutic nuclear medicine

The importance and limitations of dosimetry in the therapy of neuro-endocrine tumors with radiolabeled peptides, initially with ^{90}Y-DOTATATE/DOTATOC and currently with ^{177}Lu-DOTA-octreotate, were highlighted [86]. Higher kidney toxicity has been observed with the 90Y labelled peptides compared with the ^{177}Lu labelled peptides where it has been limited to grade 1/II toxicity. Potentially, this is due to the lower range of the ^{177}Lu beta particles compared with the range of higher energy ^{90}Y beta particles. Initial studies were performed without co-infusion of amino acids for kidney protection and since this protocol was adopted, the reported incidences of higher level toxicity have been much lower. For the ^{90}Y labelled peptide, because of the difficulties of imaging ^{90}Y, dosimetry has been sometimes performed with ^{86}Y PET, but the short half-life is a challenge. For ^{177}Lu labelled peptides, direct planar or SPECT/CT-imaging based dosimetry has been performed after treatment cycles. Comparable tumor dose – response relationships have been demonstrated for the ^{90}Y and ^{177}Lu labelled therapies. These studies typically demonstrate ~ 30% inter-patient variation in kidney absorbed doses while the variation for lesions is much higher. Recent studies have demonstrated the potential of circulating NET transcript analysis (NETest) to predict efficacy of PRRT, hence there is possibility to identify patients needing higher activity/cycles

The value of post-therapy imaging-based dose estimates in radioembolization therapy (also known as selective internal radiation therapy) of hepatic malignancies was presented [87]. Post-therapy ^{90}Y imaging based dosimetry that can be performed immediately after the RE procedure is valuable for 1) dose verification to enable early intervention when needed, 2) absorbed dose documentation that is important when retreating with radiation, and to 3) establish tumor absorbed dose – response and liver dose – toxicity relationships that can be used in future treatment planning. For establishing dose – effect, ideally direct imaging of the delivered ^{90}Y distribution by PET or SPECT should be used because of potential differences between the predicted dose distributions from a pre-therapy imaging surrogate (e.g. ^{99m}Tc MAA) and the actual delivered dose distribution. Although imaging ^{90}Y by both PET and SPECT is challenging, there have been several recent advances that have substantially improved quantitative imaging capabilities. This includes using time-of-flight PET, and Monte Carlo based methods for correcting bremsstrahlung scatter in ^{90}Y SPECT. Evidence of dose – response has been demonstrated in multiple studies.

A pilot study was undertaken on performing a selective internal radiation therapy dose calculation that compares ^{99m}Tc MAA imaging based lung shunt fraction estimated with planar and SPECT/CT imaging [88]. In the 16 patients evaluated, the lung shunt fraction calculated based on planar imaging was almost two times higher than the value estimated by SPECT/CT imaging. They predict that this overestimation by planar imaging lead to unnecessary reduction of the administered activity (underdosing) and in some cases made the patient ineligible for therapy due to concerns of high lung absorbed doses. However, during discussion it was pointed out that lung dose limits were established many years ago based on planar imaging.

In 2017, under a collaboration between the National Cancer Institutes and the University Hospital, peptide receptor radionuclide therapy with both ^{177}Lu-DOTATATE and ^{177}Lu PSMA was introduced in Uruguay [89]. Dosimetry was performed for these therapies using planar imaging with scatter and attenuation correction coupled with MIRD methodology using the tools in OLINDA. The blood-based method was used for bone marrow dosimetry. Their dosimetry results

are consistent with results in the literature. Future studies include SPECT/CT-based dosimetry and evaluation of dose – toxicity relationships.

A dosimetric analyses of critical organs (kidney, liver and spleen) of 81 patients with neuroendocrine tumors treated with ^{177}Lu-DOTATATE, was performed by coupling planar gamma camera imaging, performed at up to 9 imaging time points, with the tools in OLINDA/EXM [90]. The results demonstrate the large inter-patient variability and the estimates predict that up to 40 GBq can be administered before the renal toxicity 'limit' is reached. During the discussion there was a question on why a low-energy collimator was used for imaging ^{177}Lu, when studies have shown that the medium energy collimators are more suitable to reduce penetration effects. The response was that there was no access to a medium energy collimator. The potential for improving dose estimates by simple organ mass scaling available in OLINDA was also discussed.

The Indonesian experience with pre-therapy dosimetry for prostate cancer patients treated with ^{177}Lu - PSMA CC34 was presented [91]. The goal of the study was to establish a protocol for performing dosimetry in patients who will get ^{177}Lu PSMA TRT in the future. Previously, dosimetry has not been used in Radionuclide Therapy in Indonesia and this work was initiated with IAEA CRP E2.30.05. support. Under this protocol, 12 patients were imaged at 4h, 24h and 48h and conjugate-view imaging-based dose estimates were derived following the recommendations in MIRD 16. Results showed that kidney and liver receive the highest absorbed doses. They observed some bone uptake and they plan to further develop their methodology to include SPECT/CT imaging in order to investigate imaging-based bone marrow dosimetry.

4.3.3.Monte Carlo in nuclear medicine dosimetry

Monte Carlo has been used historically in several aspects of nuclear medicine [92]. The S-values that are tabulated for various phantoms and are routinely used in internal therapy dose estimation, are pre-calculated using Monte Carlo radiation transport in mathematical phantoms. More recently with the advances in computational power, voxel-level patient specific calculations coupling patient's own images with Monte Carlo dose estimation have become feasible, although such calculations are considered to still be too slow for routine clinical use. Because of the computational expense, Monte Carlo is only recommended when other voxel-level methods such as point kernel convolution and local energy deposition are insufficient due to tissue heterogeneities and complex geometries. Monte Carlo simulated data are widely used to test the performance of SPECT and PET imaging systems, reconstruction methods and compensation methods for image degrading physical effects. For this purpose, dedicated SPECT and PET codes such as SIMIND and SimSET, developed at single institutes, are used all over the world. In the early 2000s GATE (Geant4 Application for Emission Tomography), an opensource, freely distributed Monte Carlo simulation tool dedicated to emission tomography, was developed.

OpenDose: an Open Database of Reference Data for Nuclear Medicine dosimetry, is a free, open access data base that was launched very recently and is maintained by the collaborating researchers [93]. This is an international collaboration across 18 institutes and was initiated with the goals of generating, verifying and disseminating reference dosimetric data relevant to the nuclear medicine community. Five of the most popular MC software used in radiopharmaceutical dosimetry are included. One of the projects involves generating Specific Absorbed Fractions for different computational models and different monoenergetic radiation sources to cross check the results between different codes. The Specific Absorbed Fractions will be integrated over emission spectra to provide reference S values. Initially for this project, the focus will be on the ICRP 110 adult reference computational phantoms.

DOSIS, a patient-specific MC based dosimetry toolkit for nuclear medicine procedures, was developed for voxelized dosimetry in targeted radionuclide therapy using components from general purpose MC codes PENELOPE and FLUKA [94]. The activity and density distribution obtained from PET/CT and SPECT/CT can be coupled with the DOSIS toolbox to achieve highly patient specific dose estimates. The option to perform dose point kernel (DPK) convolution for homogeneous media is also available and work on the DPK model for non-homogeneous media is in progress. DOSIS was benchmarked with other validated MC codes and showed good agreement. The toolkit includes a Graphical user interface to facilitate the dosimetry calculation and work is also being done on implementing other features such as segmentation tools.

4.4.Dosimetry for Radiation Protection

4.4.1.Effective dose as an indicator of patient risk

The new ICRP proposals, for the use of effective dose as an indicator of harm with risk terms attributable to different effective dose ranges, were presented [95]. It was emphasized that the uncertainties associated with effective doses less than 100 mSv are very large and the corresponding risk is low. The age, sex and health status of individuals should be taken into account when considering risks, especially to patients. It was emphasized that one should not use effective dose calculations to extrapolate to future cancer risks as this was totally inappropriate for diagnostic radiology [96]. Attention was drawn to the WHO leaflets and booklet on

communicating with parents and families of pediatric patients [97] and the benefits of justified diagnostic radiology procedures, were stressed.

An estimation of whole body PET/CT combined effective doses to 170 patients was made based on the ICRP Publication No. 106 [98] dose coefficients for the radionuclides and the ICRP Publication No. 102 [99] for the CT exposures [100]. For the ^{18}F-FDG patients the combined effective dose was 18 mSv and for the ^{68}Ga-DOTATATE patients the combined effective dose was 15 mSv.

Measurements of surface doses were made using TLDs placed in the centre of the exposed field on an anthropomorphic phantom for six common radiology examinations for a range of patient exposure parameters obtained from a national survey, which was used to produce the DRLs in Ukraine [101]. Phantom simulations were then used to estimate the equivalent dose to the 12 most radiosensitive organs exposed under similar conditions. The collective effective dose for the Ukraine population was then calculated from the average effective dose and the number of procedures carried out per year [102].

4.4.2.Occupational dosimetry

The ISO/TC 85/SC 2 standards for staff radiation protection in medicine were highlighted as a newly developed set of standards related to radiation protection for individuals [103]. In the medical field, the development of new standards meets the increasing need for guidelines and protocols. It includes standards for external and internal individual monitoring of the staff, for patient dosimetry and related protocols in clinical applications and for shielding systems.

Nuclear medicine services include the preparation and administration of radiopharmaceuticals to patients. Any manipulation of radiopharmaceuticals with syringes and vials will lead to high doses to the fingers. Measures to protect the fingers include the use of tungsten shields that support the vial and provide better protection than simple lead pots, and the use of syringe shields for preparation, drawing up, and performing injections. Obtaining accurate dose assessment from routine monitoring is difficult, as the dose gradients across the hands can be substantial and the maximum dose, which is usually at the fingertips, is underestimated by ring dosimeters worn at the bases of the fingers [104]. There is a need to have a clear strategy for extremity dose monitoring.

The efficiency of different models of lead glasses in protecting the eye lenses of interventional clinicians has been assessed in a variety of ways: with phantoms, during clinical practice and with computational simulations [105]. If the dosimeter is worn under the lead glasses, the measured dose is considered to be similar to that received by the eye lens, while if the unshielded dosimeter is worn outside the glasses, a correction factor may be applied to allow for the protection provided by the glasses. However, due to the complex radiation field to which interventional clinicians are exposed, there is the potential for both approaches to underestimate the dose to the eye lens. Data suggest that a reasonable estimate of the eye dose may be derived from personal dosimeter (Hp(10)) data [106]. A study of staff member dosimetry records from two nuclear medicine units showed that the estimated annual eye lens doses seemed to stay well below the new eye lens dose limit.

4.5.Dosimetry for Radiobiology Experiments

Dosimetry is an important component in many radiobiology experiments, allowing for repeatability and valid comparison of results [107]. However, radiation dosimetry is currently not standardized and output verification in several laboratories showed large variations, especially for the medium energy kV beams [108]. The NPL reported on the need for guidelines on the dosimetry of medium energy X-ray irradiators used in pre-clinical radiation research, since the setups used for in vitro samples differ significantly from reference conditions cited in dosimetry CoPs [109]. Datasets of correction factors were calculated that will be used to develop a set of recommendations to enable the radiobiology community to deliver more accurate and harmonized dosimetry.

Microdosimetry is important since mammalian cells have typical volumes 100 - 10 000 μm^3, whereas nanodosimetry is concerned with dose deposition in volumes comparable to DNA, where the double helix diameter is approximately 2.4 nm. Traditional dose formalisms, e.g. Medical Internal radiation Dose (MIRD), assume a uniform distribution of activity and an average dose deposition per disintegration. Track structure codes can provide finer details of the nature of electron energy deposition in cells and provide information on the differences in biological effects between different radioactive isotopes. New approaches are necessary for evaluating electron emission spectra at the cellular and sub-cellular level to enhance the understanding of dosimetry of targeted therapies. A study of different iodine isotopes was presented and concluded that ^{125}I was potentially the most effective radiobiologically, compared to ^{123}I or ^{131}I [110]. Quantitative descriptions of electron transport for energies lower than 50 keV in tissue equivalent media is complex but of relevance to the use of Auger emitters in radioimmunotherapy applications. Monte Carlo calculations using PENELOPE were conducted to compare range parameters with those determined theoretically or experimentally [111].

A commercially available inorganic scintillation detector with a diameter of 1.3 mm that was characterized with medium energy X-rays [112] was described. If

cross-calibrated in the user's beam quality, it can be used for real-time, relative measurements in small animal irradiators in beams larger than 3 mm equivalent square.

V. Detector technology updates and challenges

Various types of ion chambers are used in radiotherapy and there are different criteria that should be used to select the most appropriate device to achieve an accurate dose measurement [113]. Considerations include stabilization time, polarity corrections, stability in the traceability, effective point of measurement corrections, volume averaging effects, topology and modality. The evolution of new radiotherapy treatment beams has resulted in the development of new ion chambers, which require new correction factors to accurately measure dose, especially for small fields. Cylindrical chambers with graphite walls and aluminum central electrodes appear to be the most stable chamber type in terms of longevity. It remains the responsibility of the physicist to make sure that the equipment fits the need through measurements under various conditions. This will allow the user to understand the limitations of their dosimetry equipment.

In addition to reference and relative dosimetry, various other dosimeters and dosimetry systems are used when performing dosimetry audits in radiotherapy. Selection depends on the audit complexity, accuracy desired and the reproducibility. Considerations include accuracy requirements, what it will be used for, readout procedures and analysis methods. A comparison of ion chamber and passive detector reference field output measurements between different Quality Assurance (QA) groups showed excellent agreement [114]. As the complexity of the audit increases, the choice of dosimeter, such as radiochromic film and the associated analysis method, is more crucial for good results. It was shown that different results can be obtained from using different scanning protocols, evaluation criteria and software analysis packages [115]. Comparisons of results obtained from treatment plan analyses using different detectors (film, detector arrays, ion chambers) showed differences depending on the software used to compute the gamma index, the device used and how the device was used (composite vs field by field). As a result, comparisons between external audit groups is also a challenge.

Similarly, detectors used for QC measurements in diagnostic x-ray beams have evolved into automated, multi-functional devices that display several parameters following a single exposure. These non-invasive multimeters are however not corrected for energy response and can provide incorrect results particularly at low energies, e.g. mammography [116]. There are international standards for these devices (IEC 61674 and 61676). An additional challenge is the introduction of new imaging modalities, e.g. digital breast tomosynthesis and CBCT, for which there is, as yet, no consensus dosimetry guidance.

VI. Novel dosimetry

Ion recombination issues are associated with an ultra-short high dose-per-pulse very high energy electron beam [117]. Measurements were performed with Roos type parallel plate chambers (PTW24001) in an experimental very high energy electron beam and in a 12 MeV linac beam were presented. The charge per pulse was varied along with the collecting potential. Various models were investigated to fit the measured data. There is no known acceptable model applicable to the whole data set for determining the ion recombination for the very high energy electron beams that use the ultra-short high dose-per-pulse. Findings indicated that the collecting potential needed for an accurate measurement of the collection efficiency far exceeded the ion chamber rating. These data can be used to provide a foundation for developing a new methodology to calculate the collection efficiency in these unique electron beams.

A study was conducted to assess the varying models of cross-section data used by different Monte Carlo codes on the uncertainty of microdosimetric quantities [118]. The EURADOS working group 6 launched an exercise to use various MC codes to calculate the energy distribution for three different ^{125}I source geometries (point, volume and surface configuration). The results for the point and volume sources were found to be within 2%, however, when the source was on the surface of the sphere, the deviations became significant. The origin of observed deviations is under investigation, specifically looking at the cross-section data tables used. For an ^{125}I point source in the centre of a well-defined liquid water sphere of diameter 10 micrometers, the ionization cluster size frequency distribution was calculated at different target positions and target diameters in the sphere, and large differences were observed.

Nanodosimetric track structure analysis was investigated for estimating RBE variation in a clinical proton beam. Simulations were performed using GEANT4-DNA [119]. The results showed encouraging data for the use of track characteristics predicting variations in RBE for lethal lesions in cells. The next step will be to confirm the simulations with radiobiological findings.

A study using novel photon counting pixelated detectors (cadmium telluride (CdTe) and silicon) that are capable of recording spectral information, to inform image processing algorithms to enhance CT imaging or directly correct for energy response in dose measurements [120] was described. A 0.5 mm thick CdTe chip showed

promising results when irradiated with a ^{137}Cs source. Scintillator-enhanced silicon was analyzed as a high-resolution detector and may have an application in radiotherapy fields with high gradients. Promising results were demonstrated; however, further developments and testing are needed for clinical implementation.

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