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Intercomparison and remote dosimetry audits: Safeguarding radiotherapy through global standards

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► ***Review article***

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ABSTRACT

Background: As the complexity of radiotherapy treatments increases, ensuring the quality and safety of these interventions becomes paramount. A critical component of this quality assurance (QA) is the systematic evaluation of radiotherapy processes through audits and intercomparison protocols. This has prompted the radiation authorities to establish numerous safety protocols and audit systems, thereby forming a detailed regulatory QA landscape. The present review identifies and describes the major independent dosimetry audit organisations available worldwide. ***Materials and Methods:*** A search strategy was developed and administered to select articles on dosimetry audit systems from the PubMed, Web of Science, and Scopus databases, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist. Literature searches were done using keywords like radiotherapy incident, intercomparison, remote dosimetry audit phantom, audit organisations, and radiotherapy, with an emphasis on data relevant to the research. ***Results:*** A total of 26 articles were identified that focused on the intercomparison and dose audit in radiotherapy. The reviewed articles were detailed into several groups of information, including dose audit organisation, dosimetry audit methodologies, phantoms, and approaches to dose audit. ***Conclusion:*** The existing variability in methodologies, criteria, and benchmarks across different clinical settings poses significant challenges to the consistency and reliability of QA processes. A standardised approach enables more accurate comparisons, enhances the reproducibility of audit outcomes, and promotes the sharing of best practices across institutions. This, in turn, will contribute to the overarching goal of delivering high-quality, safe, and effective radiotherapy treatments to patients.

INTRODUCTION

Radiotherapy has been a cornerstone in cancer treatment for the past decade, with advancements in technology and treatment techniques like Intensity Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) improving both precision and efficacy. Stereotactic Radiosurgery (SRS) adds another dimension to it, delivering high doses to fine targets with extraordinary accuracy to protect surrounding healthy tissue. These techniques raise the ceiling to dose deliverable per fraction for higher tumour doses while minimising any complications. However, even minor deviations in dose delivery can result in considerable clinical consequences. This reiterates the critical need for stringent quality assurance protocols to ensure accurate dose delivery [1-3].

Quality assurance (QA) is the backbone of radiotherapy that ensures consistency through intercomparison and dosimetry audit protocols. These independent evaluations assess whether the beam output calibration in clinical settings adheres to the global recommended level, thus ensuring accuracy and consistency. Therefore, audits are typically conducted by national or international organisations or through peer reviews by external radiation physicists to compare a centre's dose measurements against those obtained using standardised methods and equipment. The goal is to verify that the delivered doses align with established guidelines and global dose limits, ensuring patient safety and adherence to best practices [4-6].

Dosimetry audits systematically evaluate radiotherapy processes, equipment, and protocols. The aim is to identify and rectify discrepancies in

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dose delivery, thus preventing errors that could compromise treatment outcomes. However, the global implementation of these audits lacks uniformity. Differences in methodologies, benchmarks, and criteria between institutions create challenges for comparability and harmonisation. This variability undermines the goal of consistent, high-quality radiotherapy across diverse clinical environments [7-9].

To address these challenges, there is a growing need to consistent intercomparison and audit protocols. Establishing uniform guidelines will enable reliable evaluations and foster international collaboration, which will enhance the comparability of audit results, streamline QA processes, and promote equitable access to high-quality radiotherapy. This review explores existing dosimetry auditing techniques and highlights their strengths and limitations, aiming to support the development of effective protocols that can enhance patient care [10, 11]. The novelty of this study lies in its identification of inconsistencies in methodologies, criteria, and benchmarks across different audit organisations. It also enhances reproducibility and strengthens cross-institutional quality assurance in radiotherapy by emphasising the urgent need for a standardised approach to dosimetry audits.

MATERIALS AND METHODS

Search strategies and information sources

A systematic analysis of past literature was conducted by employing data from several electronic databases, including PubMed, Web of Science (WoS), and Scopus. The literature search focused on recognising the extensive examination and analysis of intercomparison and dose audit studies published from 2003 to December 2023. Keyword phrase searches and Medical Subject Headings (MeSH) terms like "radiotherapy", "dosimetry", "phantoms", "quality assurance", and "radiotherapy dosage" were used to identify relevant publications. All keywords were related to radiotherapy intercomparison and dose audits. Only English-language articles were included and the reference lists were also manually reviewed to identify potentially eligible studies.

Selection criteria

All radiotherapy-related intercomparison and dose audit studies found during the literature search met the inclusion criteria. However, the following research was excluded from this study: i) studies connected to brachytherapy, tomotherapy, and gamma knife; ii) outdated research (articles published before 2003); iii) abstracts from conferences that do not provide full-text articles or detailed data; iv) studies that do not focus on clinical radiotherapy practices, such as purely theoretical papers, and experimental physics studies without clinical application.

Data extraction for study selection

The initial results from the systematic literature search were imported into Mendeley Desktop version 2.106.1 (Mendeley Ltd., United Kingdom). After identifying and removing duplicates, the remaining titles and abstracts were thoroughly reviewed for inclusion in the research. The full-text articles were then extracted and manually reviewed for relevance. The data was extracted using structured approaches and compared separately to verify correctness. Any inconsistencies discovered throughout this procedure were thoroughly investigated and rectified. The objectives of all selected articles were carefully reviewed to determine their relevance to this review paper. It was followed by extensively reviewing and synthesising the research objectives, procedures, approaches, major results, and suggestions. Subsequently, a conclusion was devised using the defined research criteria.

RESULTS

Literature search

A total of 137 articles were obtained from the literature search. The abstracts were chosen for a final review after a preliminary database search (figure 1). Articles that met the selection criteria were included in the review. Conversely, 25 duplicates were removed and cross-checking of the abstracts resulted in 112 articles. A comprehensive examination of the entire text and data for completeness led to the further elimination of 86 studies, resulting in 26 articles for the review.

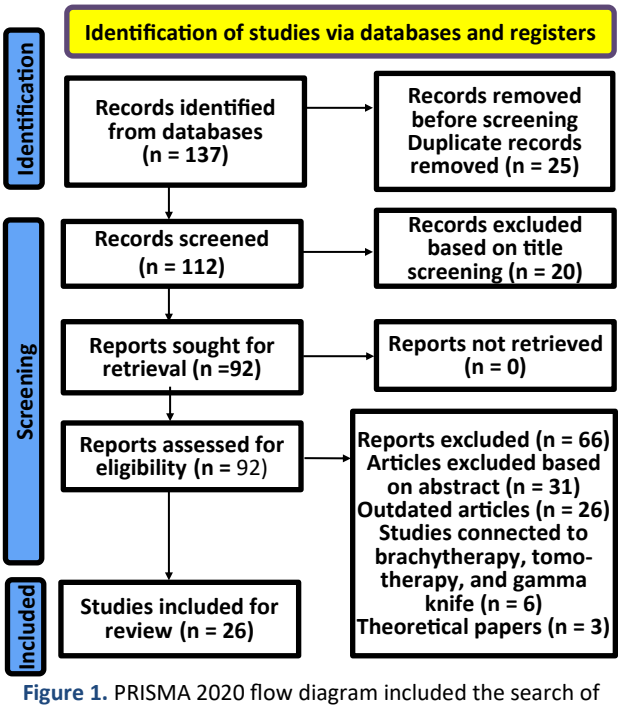

Figure 1. PRISMA 2020 flow diagram included the search of databases and registers.

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International dosimetry audit and intercomparison services

An external dosimetry audit at the institutional level provides an independent check of the in-house dosimetry chain through standardised measurement protocols that provide traceability to a primary standard. Several organisations conduct intercomparison and dose audits to compare the observed absorbed dose of one hospital to a known standard, hence measuring dosimetry precision within the radiation network. The audit guidelines for radiotherapy treatment machines are provided by national and international organisations around the world. Currently, radiation dosimetry protocols for dosimetry audits are established by international radiation regulatory bodies (e.g., the International Atomic Energy Agency (IAEA)) or continent professional organisations (e.g., the Australian Clinical Dosimetry Service (ACDS) and the Imaging and Radiation Oncology Core (IROC) Houston). These organisations collectively contribute to the development of international best practices, providing the necessary infrastructure and expertise to maintain high levels of accuracy and safety in radiotherapy [12].

Regular dosimetry auditing is vital to ensure accurate radiation dose delivery in external beam radiotherapy. The audit involves comprehensive evaluations of the radiotherapy process [13, 14], ranging from basic checks of reference dosimetry to advanced assessments of end-to-end dose delivery (figure 2). Using the applicable code of practice, a reference dose audit (Level I) confirms that treatment equipment has been calibrated accurately. Meanwhile, a Level II audit investigates the commissioning data and the construction of the treatment planning system (TPS) beam model. Phantom is commonly used in Level III audit, which passes through the whole chain of events that a patient will undergo during radiotherapy simulation, planning, and treatment [15]. In an ideal world, the evaluation should be sensitive to detecting dosimetry problems regardless of audit level, with a focus on consistency in findings across different worldwide dose audit groups. The global harmonisation group discusses and highlights the need of preserving uniformity in the conclusions of various worldwide QA organisations [16].

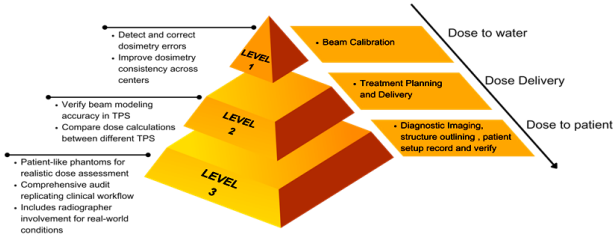

Figure 2. The pyramid of dosimetry audit in radiotherapy explaining the multi-tiered approach to quality assurance.

Remote dosimetry audit

Despite the foundational tiered approach to QA in radiation audits implemented by independent organisations, a more comprehensive and specialised protocol is required to guarantee that it is tailored to the needs and challenges of designing and running effective dosimetry audits. While IAEA, ACDS, and IROC have the same goal of certifying dosimetry accuracy, their approaches differ in small but significant ways, thus influencing the scope and focus of their audits. In 2001, IAEA initiated a coordinated research project (CRP) that broadens the scope of activities of thermoluminescence dosimeter (TLD) based national dosimetry audit program in radiotherapy from reference conditions to more complex audit measurements, which is clinically relevant to the sophisticated irradiation geometries like irregular field set-up. The current strategy for the TLD dose audit program, which consists of nine sequential audit steps [16], adheres to the overarching idea of the IAEA audit program's step-by-step advancement of audits for increasing layers of complexity in radiotherapy dosimetry.

ACDS is one of the leading organisations that provides structured dosimetry audit programs to assure the accuracy and safety of radiotherapy treatments. Hierarchical audit frameworks are used to assess and verify the performance of radiation facilities, with each level becoming more complicated and comprehensive. It begins with a basic assessment of the output of the linear accelerator (linac) and progresses to end-to-end testing of the complete radiotherapy process, from treatment planning to dose delivery [17, 18]. IROC Houston, part of the National Cancer Institute's (NCI) QA program for clinical trials, also offers a multi-level audit system and credentialing program, which primarily focuses on ensuring the uniformity and accuracy of radiotherapy across institutions involved in clinical trials. They conduct a variety of phantom-based audits [19-21] where institutions irradiate anthropomorphic or geometric phantoms according to prescribed treatment plans. The phantom audits are often tailored to specific treatment techniques, such as IMRT, stereotactic body radiation therapy (SBRT), or proton therapy.

Table 1 shows the remote audit performance from different bodies. IAEA conducted the most comprehensive audits but had a lower average pass rate compared to ACDS. IROC audited the most facilities but had a broader range in pass rates. The differences in remote dosimetry audit performance across IAEA, ACDS, and IROC can be attributed to audit protocol where IAEA's thorough approach likely introduces more variables and complexities, making it harder for facilities to achieve a perfect score. Meanwhile, the more complex and comprehensive criteria used by IROC might set a higher bar for compliance, making it more

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challenging for facilities to pass. ACDS might have more specialised expertise in conducting audits that align closely with specific national or regional standards, potentially leading to higher compliance rates.

Table 1. Performance comparison of remote audits by IROC, ACDS, and IAEA.

Organisation	Remote dosimetry audit protocol	Audited facility in 2022	Average pass rate (%)
IAEA	Nine sequential audit steps covering: reference and non-reference conditions. irregular and heterogeneous beams. small fields.	~300	90
ACDS	Output check on reference beam.	117	95
IROC	Output check on reference beam.	569	85 -95

Note: IAEA: International Atomic Energy Agency; ACDS: Australian Clinical Dosimetry Service; IROC: Imaging and Radiation Oncology Core.

Reference dose audit

Reference dose audit is a crucial quality assurance step to ensure that doses prescribed by oncologists and calculated by treatment planning systems are accurately delivered by radiotherapy equipment like linear accelerators. This process typically uses calibrated dosimeters to measure machine output, ensuring compliance with both national and international standards. Reference dose audit is essential for routine clinical practice and maintaining consistency in multi-centre clinical trials where uniform dosing across different facilities is key. As radiotherapy techniques become more advanced, the role of reference dose audit grows more important, providing a solid framework to verify the precision of complex treatment plans and supporting safe, effective treatment delivery.

While international organisations offer reference dose audits, their methods can differ. IAEA prioritises accuracy by using sophisticated dosimeters like TLDs, optically stimulated luminescence dosimeters (OSLD), and radiophotoluminescence dosimeters (RPLD) placed deep within a standard field to simulate real-world treatment scenarios [22]. ACDS focuses on practicality and uses simpler OSLDs placed on the surface, making handling easier and improving data comparison across centres [23]. IROC takes a tailored approach by using either TLDs or OSLDs based on radiation type (photons or electrons) and adjusting placement depth accordingly [19]. These differences reflect each organisation's priorities: IAEA aims to replicate clinical conditions, ACDS emphasises ease of use for broader participation, and IROC tailors the audit to the specific radiation type for more detailed assessments. Table 2 summarises these practices, helping radiotherapy centres choose the most suitable audit service for their needs.

Phantom for advanced dosimetry audit

Dose audits in radiotherapy are diverse, with various organisations developing specialised phantoms for accurate and consistent dose verification. Through coordinated research and clinical trials, these organisations have created phantoms that can perform precise audits, helping centres assess their treatment plans and implement corrective actions when needed. For instance, a previous study using an anthropomorphic head and neck phantom with TLDs achieved dose verification within ±4% of planned doses [24]. Radiotherapy centres looking to evaluate and optimise their treatment plans have a range of options available. Table 3 highlights some of the leading phantoms developed by these organisations, illustrating the variety and sophistication of these essential audit tools.

Table 2. Comparative analysis of reference dose audit by IAEA, ACDS, and IROC.

Parameter	IAEA	ACDS	IROC
Beam type	Photon Electron	Photon Electron FFF	Photon Electron
Dosimeter	TLD OSLD RPLD	OSLD	TLD OSLD
Depth (cm)	10	Surface	Surface
Field size (cm^2)	10 × 10	10 × 10	10 × 10
Distance	Nominal SSD or SAD distance	100 cm SSD	Nominal SSD or SAD distance
Dose or monitor unit	2 Gy	100 MU	3 Gy for TLD 1 Gy for OSLD
Acceptable deviation	±5%	±3.9% (Photon) ±5.1% (Electron)	±5%
Frequency	By request	Every alternate year	Annual
Audit coverage	IAEA member states	Australia and New Zealand	North American

Note: TLD: Thermoluminescence dosimeter; OSLD: Optically stimulated luminescence dosimeter; RPLD: Radiophotoluminescence dosimeter; SSD: Source-to-surface distance; SAD: Source-to-axis distance; FFF: Flattening filter-free.

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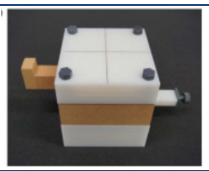
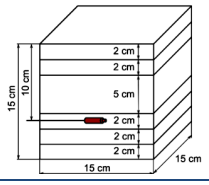
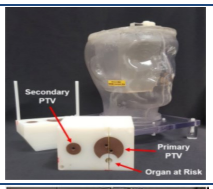
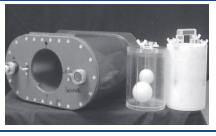
Table 3. Overview of the phantom specifications developed by IAEA, ACDS, and IROC through coordinated research programs.

Reference	Type	Phantom	Description
IAEA			
IAEA [16]	Solid phantom		A solid phantom was developed to facilitate dose audits in scenarios with varying materials (heterogeneity). This phantom, features two configurations: a uniform polystyrene setup and one with lung-mimicking cork material. Both configurations are designed to accommodate TLDs for accurate dose measurements.
	IMRT phantom		The phantom includes an internal insert filled with TLDs for precise dose measurements. Additionally, a separate pillbox containing TLDs can be attached to the exterior for more thorough analysis. The disassembled view highlights the internal insert, demonstrating its ability to accommodate both film and TLDs for detailed evaluation.
	Solid slab polystyrene phantom		This phantom consists of polystyrene slabs with inserts mimicking lung and bone tissues and creates various tissue density scenarios. One TLD resides in a central polystyrene section, while another sits off-centre within the lung-mimicking insert.
ACDS			
Lehmann *et al.* 2018 [25]	Multimodality		This custom tool is versatile enough to handle audits for techniques, such as conformal therapy, IMRT, VMAT, and SBRT. Its design is future-proof, allowing the integration of motion and 4D IGRT audits.
IROC			
Desai *et al.* 2021 [26], Mehrens *et al.* 2022 [27]	SRS head		The phantom includes an imaging insert compatible with both CT and MRI scans, ensuring accurate treatment volume definition. It also features a dosimetry insert that holds radiochromic film and TLDs, allowing for a detailed assessment of radiation dose distribution during treatment.
Carson *et al.* 2016 [28]	Head and neck IMRT phantom		The phantom comes with an imaging insert compatible with both CT and MRI scans, ensuring a precise definition of the treatment volume. Additionally, it includes a dosimetry insert designed to hold radiochromic film and TLDs, providing a comprehensive analysis of radiation dose distribution throughout the treatment process.
Edward *et al.* 2020 [29], Desai *et al.* 2024 [30]	Lung-spine phantom		Lung-spine phantom mimics real patients and is specifically designed to test radiotherapy procedures for lung cancer. It challenges imaging, treatment planning, and dose delivery systems, ensuring accurate targeting of tumours while minimising harm to surrounding healthy tissues.
Taylor *et al.* 2021 [31]	Liver phantom		This phantom replicates a human liver with two designated target areas and two organs at risk, allowing for comprehensive testing of treatment planning and delivery systems.
Ibbott *et al.* 2006 [32]	Pelvic-prostate phantom		This phantom features a realistic pelvic shell, an imaging insert containing a prostate, rectum, and bladder, and a dosimetry insert with specialised film and detectors for accurate dose measurement.

Note: TLD: Thermoluminescence dosimeter; IMRT: Intensity-Modulated Radiation Therapy; VMAT: Volumetric Modulated Arc Therapy; SBRT: Stereotactic Body Radiation Therapy; IGRT: Image-Guided Radiation Therapy; CT: Computed Tomography; MRI: Magnetic Resonance Imaging; SRS: Stereotactic Radiosurgery.

DISCUSSION

Advanced radiation therapy techniques, such as Volumetric Modulated Arc Therapy (VMAT) and Intensity Modulated Radiation Therapy (IMRT) [33, 34], have significant complexities. The modulation of multiple parameters in VMAT and IMRT introduces dosimetric challenges, increasing the risk of errors that can impact treatment accuracy and patient safety. A structured governance framework is essential to manage these challenges effectively, encompassing rigorous quality assurance measures, standardisation of practices across institutions, and improved training for clinicians and medical

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physicists. However, ensuring compliance with these standards across diverse clinical settings requires independent verification and oversight.

This is where dosimetry audit organisations play a critical role. Entities like IAEA, ACDS, and IROC have established standardised protocols and conducted external audits to validate treatment accuracy, reducing the risk of errors and discrepancies in dose delivery. Through rigorous QA measures, these organisations ensure that dosimetric accuracy translates from treatment planning to clinical practice, ultimately improving patient safety [35-37]. While the need for robust dosimetry audit systems is well established, the effectiveness of these systems varies depending on the audit organisation. Differences in scope, methodology, and regional influence can impact their ability to standardise radiation dosimetry worldwide. Figure 3 shows a comparative performance analysis of IAEA, ACDS, and IROC to assess their strengths and limitations.

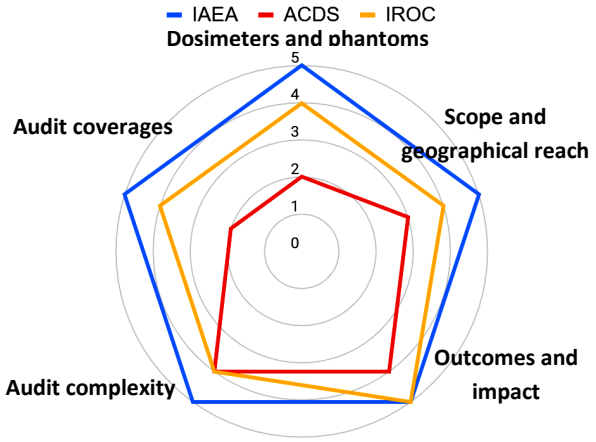

Figure 3. Radar chart comparing the performance of IAEA, ACDS, and IROC dosimetry audit programmes.

middle-income countries can uphold high standards of radiation safety despite resource constraints. While ACDS remains an essential auditing body, its reach is more localised, primarily focusing on Australia and nearby regions. It operates with a more specialised approach, potentially conducting audits with less complexity and narrower geographical coverage. In contrast, IROC integrates its audit services within a robust network of research and clinical institutions, providing comprehensive support to many radiation oncology centres. Its strength lies in the ability to facilitate large-scale clinical trials and audits that enhance the precision of advanced radiotherapy techniques.

As radiotherapy evolves, consistent dosimetry audits are essential for ensuring dose accuracy and minimising errors that may compromise treatment efficacy [38-40]. Aligning dosimetry protocols across both therapeutic and diagnostic applications strengthens radiation protection measures and quality assurance frameworks. This ensures consistent dose assessments and regulatory compliance across institutions. By adhering to established guidelines, standardisation improves radiological procedures, minimises unnecessary radiation exposure, and preserves diagnostic accuracy. It facilitates the effective implementation of regulations, improving public health and clinical outcomes through better dose monitoring and comparison with diagnostic reference levels (DRLs) [41]. Furthermore, harmonisation fosters collaboration among professionals, encourages knowledge sharing, and builds public trust by ensuring adherence to established safety benchmarks. Ultimately, maintaining consistency in dosimetry practices is crucial for delivering safe, high-quality healthcare and ensuring patient safety across radiotherapy and imaging practices [42].

Several recommendations are proposed to address the challenges posed by the lack of harmonisation in dosimetry audit protocols and procedures across radiation organisations worldwide. Developing standardised dosimetry audit protocols will improve global consistency in radiotherapy QA. A global network of radiation audit organisations can facilitate communication, data sharing, and collaborative audits, thus ensuring a more unified approach [43-45]. Establishing a centralised database for dosimetry audit results will facilitate global data-sharing, enabling continuous quality improvement in radiotherapy [46]. By consolidating audit data across different regions, such a system will help identify trends, improve safety protocols, and support research aimed at minimising treatment uncertainties. Measures like regular workshops, conferences, and training programs focusing on harmonising protocols and procedures will further support this goal.

A global accreditation system for radiation audit organisations can establish uniform quality benchmarks, ensuring all entities adhere to high dosimetric accuracy standards. Accreditation within existing audit frameworks will improve trust and collaboration in global radiation safety [47]. Strengthening partnerships between international radiation safety and dosimetry bodies, such as the International Commission on Radiation Units and Measurements (ICRU) and the International Commission on Radiological Protection (ICRP), will help unify efforts in protocol development and auditing. Furthermore, making audit results publicly available will encourage transparency and accountability and foster trust among institutions. Finally, a commission should be established for the continuous review and updating of dosimetry audit protocols to ensure that they evolve with technological advancements and clinical needs.

Integrating advanced computational techniques, such as Monte Carlo simulations, into radiation audits can further enhance dosimetric accuracy and quality assurance. Monte Carlo simulations can be potentially

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integrated into a virtual audit system to allow remote and automated verification of treatment planning and delivery. A virtual audit system using Monte Carlo models provides institutions with rapid feedback on dose accuracy without requiring physical measurements [48, 49], thus reducing logistical constraints and operational costs. Such a system also enables continuous quality control, allowing clinics to identify discrepancies early and make necessary adjustments before patient treatment. By leveraging Monte Carlo simulations for virtual audits, radiation oncology centres worldwide can enhance dosimetry accuracy, standardise quality assurance practices, and improve overall patient safety in radiotherapy.

This comparison underscores the importance of a multi-tiered approach to dosimetry oversight. International organisations like IAEA and IROC can provide a global framework, guidance, and expertise, while national bodies like ACDS ensure compliance with national regulations. International proficiency testing programs offered by IROC can further strengthen national programs by identifying areas for improvement and promoting best practices. By working together, these organisations can ensure the accuracy and consistency of dosimetry programs worldwide, ultimately contributing to better radiation protection. However, this study primarily focuses on the dosimetry audit frameworks of IAEA, ACDS, and IROC, which, while significant, do not fully capture the contributions of other audit organisations worldwide. Including additional entities such as the European Society for Radiotherapy and Oncology (ESTRO), the Japan Society of Medical Physics (JSMP), and the Secondary Standard Dosimetry Laboratories (SSDL) network would provide a more comprehensive perspective on global dosimetry practices and enhance the study's applicability across diverse clinical settings.

CONCLUSION

Radiotherapy demands precise and consistent dosing, which can be achieved through intercomparison and dose audits. This study examines independent audit procedures and highlights the associated strengths, limitations, and research opportunities. Dosimeters and phantoms are central to audits and have been evolving to address patient-specific complexities. Advancements in dosimeter design and methodology offer complementary benefits; nevertheless, standardisation of techniques and data analysis remains a challenge. Ultimately, harmonisation is crucial to ensure uniformity across audits and organisations.

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Conflict of Interest: The authors declare no conflict of interest.

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