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From the Editor

This year the IAEA/WHO postal dose audit service is celebrating its 50th anniversary. This special issue of the SSDL Newsletter (No. 70), dedicated to the dosimetry audits, has been produced to mark this special occasion. Over the last 50 years, thousands of hospitals and SSDLs have benefited from this service which has improved the consistency of dosimetry and ensured the quality of treatment for patients in Member States.

The special issue was compiled by Joanna Izewska, the former head of the IAEA Dosimetry Laboratory. With long years of experience in the field of audits, Ms Izewska has

been a leading force in the work conducted to support the strengthening and expansion of dosimetry audits worldwide. This Newsletter contains articles from across the world and provides a general overview of this topic. Acknowledgement goes to Noura El-Haj of the Division of Human Health for editing authors' contributions.

This issue is testament to the significance of audit services and the excellent efforts exerted by the many people who are passionate about continuously improving the quality of dosimetry for the benefit of patients.

Paula Toroi, the SSDL Officer



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Services provided by the IAEA in DMRP Section

The IAEA's Dosimetry and Medical Radiation Physics Section focuses on services provided to Member States through the IAEA/WHO SSDL Network and on a system of dose quality audits. The measurement standards of Member States are calibrated, free of charge, at the IAEA's Dosimetry Laboratory. The audits are performed through the IAEA/WHO postal dose audit service for SSDLs and radiotherapy centres by using radiophotoluminescence and optically stimulated luminescence dosimeters (RPLDs and OSLDs).

The Dosimetry Laboratory's Quality Management System has been reviewed and accepted by the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB). The IAEA Calibration and Measurement Capabilities (CMCs) have been reviewed and published in Appendix C of Comité International des Poids et Mesures (CIPM), Mutual Recognition Arrangement (MRA).

The IAEA CMCs can be found at the following web site: <http://kcdb.bipm.org/AppendixC/search.asp?met=RI>

The range of services is listed below.

| <i>Services</i> | <i>Radiation quality</i> |
|---|--|
| Calibration of ionization chambers (radiation therapy, radiation protection, and diagnostic radiology including mammography)* | X rays and γ rays from ^{137}Cs and ^{60}Co |
| Comparison of ionization chamber calibrations coefficients (radiation therapy, radiation protection, and diagnostic radiology including mammography) for SSDLs* | X rays and γ rays from ^{137}Cs and ^{60}Co |
| Dosimetry audits (RPLD) for external radiation therapy beams for SSDLs and hospitals** | γ rays from ^{60}Co and high energy X ray beams |
| Dosimetry audits (OSLD) for radiation protection for SSDLs | γ rays from ^{137}Cs |
| Reference irradiations to dosimeters for radiation protection | X rays and γ rays from ^{137}Cs and ^{60}Co beams |

* Technical procedures and protocols for calibrations and comparisons are available on our website <https://ssdl.iaea.org/>

**Thermoluminescence dosimeters (TLDs) were replaced by RPLDs in 2017.

Member States interested in these services should contact the IAEA/WHO SSDL Network Secretariat, for further details, at the address provided below. Additional information is also available at the web site: <https://ssdl.iaea.org>

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Note to SSDLs using IAEA calibration and audit services:

1. To ensure continuous improvement in IAEA calibration and audit services, SSDLs are encouraged to submit suggestions for improvements to the Dosimetry Contact Point.
2. Complaints on IAEA services can be addressed to the Dosimetry Contact Point.

Introductory remarks

J. Izewska

International Atomic Energy Agency

This Special Issue of the SSDL Newsletter was prepared to commemorate the 50th anniversary of the IAEA/WHO postal dose audit service. The year 1969 has been marked as the beginning of the regular auditing service by the IAEA/WHO. That year the batch #1 of thermoluminescence dosimeters (TLDs) was sent to a group of radiotherapy centres within the project called “Joint IAEA/WHO Dose Intercomparison Service for Radiotherapy”. The idea of organizing dosimetry audits for radiotherapy centres by the IAEA, was discussed in late 1950s, i.e. over 70 years ago. The IAEA Dosimetry Laboratory was established in 1961 with the purpose to design a calorimeter for dosimetry comparisons and prepare a dedicated dosimetry system suitable for postal dose audits. First pilot postal dose inter-hospital comparisons were conducted by the IAEA in 1965–1966 involving Fricke dosimeters and TLDs. Eventually, the service was established based on TLDs due to the adequate precision, low cost and easiness of shipment and it has been operated this way until 2016. In 2017 the IAEA phased out its aging TLD readers and upgraded the lab equipment by acquiring new radiophotoluminescent dosimetry (RPLD) systems. WHO joined the project in 1968 and since then it has co-operated for the implementation of auditing services. In particular, the Pan-American Health Organization actively supports audits in Latin America and the Caribbean. Relevant commemorative statements are given by the IAEA/WHO in this issue of the Newsletter.

The significance and impact of dosimetry audits are discussed by D. Thwaites in this issue. Statements are provided by the Global Harmonization Group for Radiotherapy QA and the European Society for Radiotherapy and Oncology who have strong interests in dosimetry audits, in particular for modern technologies in radiotherapy. The IAEA anniversary article discusses historical developments and present activities of the IAEA/WHO dosimetry audit service, including the results and lessons learnt over the years. The IAEA support in development methodologies for dosimetry audit networks (DANs) is briefly reviewed. Several examples of DANs are presented with the largest audit programme conducted by the IROC-Houston QA Center, USA, that serves radiotherapy hospitals in North America and several other countries. DANs of Argentina, Australia, Belgium, Czech Republic, France, Germany, Greece, Japan, Mexico, Poland, the Netherlands and UK provided their contributions to this issue. New IAEA end-to-end intensity modulated radiotherapy (IMRT) audits are also shortly presented with an example of a national audit implementation in Portugal.

In addition to audits that focus on dosimetry and medical physics topics, a comprehensive audit methodology was developed by the IAEA within the framework of the Quality Assurance Team for Radiation Oncology (QUATRO). As of 2005, close to 100 QUATRO audit missions have been implemented and a brief overview of these activities is also included in this Special Issue of the SSDL Newsletter.



The IAEA Audit Team, March 2019, from left to right: A. Baumgartner (Consultant), J. Izewska (Head, Dosimetry Laboratory), A. Pirkfellner (Dosimetry Services Assistant), T. Bokulic (Dosimetry Specialist), P. Wesolowska (Dosimetrist), P. Kazantsev (Dosimetrist).

Statement by May Abdel-Wahab, Director, Division of Human Health, IAEA



Welcome to this special Issue of the SSDL Newsletter covering the 50-year anniversary of the IAEA/WHO postal dose audits. As we continue to move forward together and collaborate as one world, we must reflect on past accomplishments and look forward to future opportunities for service and collaboration.

We are aware of the contributions of the IAEA/WHO postal dose audit service on which over 2300 radiotherapy centres in 135 Member States have relied since 1969. Over the years, audits have improved dosimetry practices and the accuracy of dose measurements in many radiotherapy centres. The audit process also helps maintain the quality of dose measurements. Consistent methods of measuring and prescribing and reporting radiation doses given to cancer patients are essential for the accurate delivery of radiation treatments. The resulting accuracy, reliability and reproducibility in the determination of radiation doses are essential components to ensure safe and high-quality treatment as well as an optimal outcome for each patient.

As a radiation oncologist, one acutely understands the impact of such dosimetry audits, as they provide confidence in the quality of clinical dosimetry. Audits provide dependable support to one of the basic tenets of quality and safety in medical practice- delivering the right dose. This improved consistency can inevitably affect outcomes of cancer patients treated with radiation.

It has been inspiring to observe the expansion of services within the Seibersdorf Dosimetry Lab, as well as the exciting training opportunities and applied research occurring there. In addition, the SSDL Network colleagues world-wide continue to work tirelessly to provide essential services and collaborate extensively. I would like to acknowledge the excellent leadership of Joanna Izewska, the IAEA Dosimetry Lab head who is retiring after 23 years and thank her for her long service and dedication.

The future holds opportunities for new services, especially with the installation of the new Varian True Beam linear accelerator at the Seibersdorf laboratory, which includes SBRT capability, and the recent availability of HDR brachytherapy.

As we look to the future, we are pleased to continue to work together to make radiotherapy safer for patients world-wide by ensuring the accuracy of the basic building block of radiotherapy.

Statement by Debbie van der Merwe, Head, DMRP Section, IAEA



Celebrating 50 years of the IAEA/WHO dosimetry audits is an important milestone. This endeavour has provided assurance of accurate reference dosimetry in many radiotherapy centres around the world which in turn, indirectly impacts on the treatment of millions of patients worldwide. Over the years, the demand for dosimetry audit services has grown and the IAEA has assisted

in the establishment of several national dosimetry audit networks, who provide national and sub-regional services to hospitals.

A significant amount of resources goes into the administration of the service, the process of identifying and characterizing each dosimeter, checking that the results are correct before the certificates are issued to the hospitals, and assisting medical physicists in Member States who have discrepancies in their results. In addition, for the past 25 years, the laboratory team has also coordinated and supported research projects to develop, conduct and disseminate audit methodologies for a range of techniques, which can be used to audit the entire radiotherapy process. A highly sophisticated and effective system of dosimetry auditing has been developed at the Dosimetry Laboratory over the past 50 years, for which a special thanks is due to the dedication and commitment of the staff.



50 years of the IAEA/WHO postal dose audit service

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The World Health Organization (WHO) joins the International Atomic Energy Agency for the commemoration of the 50th Anniversary of the IAEA/WHO postal dose audit service.

In 1968, a seminal meeting on dosimetry requirements in radiotherapy centres took place in Caracas, Venezuela, with participation from the IAEA, the Pan American Health Organization (PAHO), and the WHO. One of the recommendations of the meeting included the creation of regional dosimetry laboratories. In 1969, the WHO established the first Regional Reference Centre for Secondary Standard Dosimetry (SSD) within the laboratories of the Atomic Energy Commission of Argentina. In 1976 the IAEA/WHO Network of Secondary Standards Dosimetry Laboratories (SSDLs) was established. A periodic newsletter of the SSDLs was published by WHO until 1986, at which time the IAEA took over the responsibility.

The IAEA/WHO postal dose audit service supports medical facilities using Co-60 therapy units and clinical accelerators, monitors activities of the SSDLs regarding radiotherapy, and audits radiation protection standardization in SSDLs. This

audit service has validated the calibration of radiation beams in all regions of the world and became the most comprehensive and reliable global service of quality audits in dosimetry for radiation medicine. It has provided a benchmark for dosimetry standards and calibration services and consolidated key attributes such as traceability, accuracy, consistency and cooperation.

WHO relies on this global platform to ensure quality and safety for billions of patients diagnosed and treated in radiation medicine services worldwide. In addition to the provision of dose quality audit services, it contributes to disseminate knowledge, improve the accuracy of radiation measurements, facilitate links between end-users, provide support on calibration and dosimetry, identify research needs and promote consistency of radiation measurements.

WHO greatly appreciates this successful longstanding collaboration and looks forward to continuing and strengthening the collaboration with the IAEA in this field, to enhance quality and safety in the in the medical use of radiation.



WHO Headquarters, Geneva, Switzerland



PAHO Headquarters, Washington, USA

The significance and impact of dosimetry audits in radiotherapy

D. I. Thwaites

University of Sydney, Australia; University of Leeds, UK

Accuracy, quality assurance and quality audit in radiotherapy

Radiotherapy (RT) is a safety-critical use of high-dose radiation and requires clear and consistent methods of measuring, describing, prescribing, modelling, delivering and reporting dose, so that individual treatments can be safely and accurately delivered and clinical experience can be confidently shared between centres at local, national and international levels [1]. A high degree of accuracy, precision, reliability and reproducibility is required in the radiation dose delivered to patients and in the inter-linked geometric and spatial treatment parameters. The overall accuracy in the radiation dose delivered to the patient dose specification point is generally recommended to be within $\pm 5\text{-}6\%$ of prescription at the 95% confidence level [2, 3]. This requires smaller uncertainties in each step of the complex dosimetry chain and of the whole RT process that contributes to the final accuracy. In turn this requires continued detailed quality assurance (QA) of each component. On-going QA also minimizes the possibility of unintended exposure, either of overdose which can cause significant damage to normal tissues or, conversely, of underdose which can compromise treatment objectives. There are many sets of recommendations on QA of equipment, procedures, processes, etc. from national and international bodies. Over the last decades these have increasingly been set within wider quality management systems (QMS) covering all the steps from treatment decision and prescription, up to dose delivery and follow-up (e.g. the ESTRO recommendations [4, 5], taken into account in many European QMS guidelines). One necessary component of a QMS is internal and external system audits. An independent external audit is an effective method of checking that the quality and accuracy of activities in an individual institution are suitable for achieving the required objectives. Quality audits in RT can be of a wide range of types and levels, either reviewing the whole process (e.g. the IAEA QUATRO audit programme [6]) or specific critical parts of it. However, the first external audits in RT were specifically for dosimetry and the wider concepts of audit in RT have largely developed out of such long-standing medical physics audits.

Dosimetry audit in radiotherapy

This issue of SSDL Newsletter, celebrating 50 years of the IAEA work in dosimetry audit, contains reviews of the current status of a range of dosimetry audit programmes.

Some are for routine department dosimetry, some are specifically for clinical trials [7]. Almost all started with auditing only RT dose in reference conditions. Increasingly audits of other parameters have been included, separately or in combination, to more closely approach the levels of dose delivery to the patient and to respond to the demands of evolving complexity of RT and advanced treatment techniques [8]. Many of the audit networks have cooperated, to compare their performance and results to ensure that there is a close correspondence in outcome and that they are working to the same minimum levels and standards. This is a further powerful tool to ensure the consistency of quality in dosimetry in RT centres world-wide. The IAEA supports these efforts by providing reference irradiations and blind tests to verify the quality of the operation of dosimetry systems used by national audit centres [9]. More recently these growing collaborations have been formalised within the Global Harmonisation Group [10].

What has the impact of dosimetry audits been?

Firstly, in every dosimetry audit programme, measured doses have been observed and reported which have been outside the required tolerances and in some cases significantly so [11, 12]. Therefore, audits have been directly effective in identifying problems and providing support to finding the source of the problems and to rectify them. Thus audits have improved practice and the accuracy of dosimetry in a wide range of RT centres. As part of that, audits can reduce the likelihood of accidents and errors occurring or continuing, by identifying underlying problems, thereby reducing their consequences for patient treatment. Audits close the dosimetry QA loop by testing that the activities relating to dose can be demonstrated to ensure delivery of what is intended. They provide independent assessments of methods, procedures, processes and data, by verifying effectiveness and performance of the overall approach. Audits help in reducing uncertainties and in increasing the precision and consistency of RT dosimetry between centres. They also improve practice over time and help in maintaining that; e.g. all audit systems have reported better overall performance at later audits than in the earlier rounds, or that performance of individual centres is improved at follow-up audits [11, 12]. This is partly because errors identified earlier are rectified and partly because audits give an impetus to departments to focus on quality and performance in a way that continues to deliver benefit. Audit can also provide support and confidence for the introduction

of new and complex processes and technologies [7]. Whilst more complex treatments can produce more targeted RT treatment, at the same time they have the scope for additional problems and so require more complex QA. Therefore, the gradual development and extension of the scope of dosimetry audits, from initially of beams in reference conditions, to include more parameters of dosimetry, equipment performance, complex irradiations and advanced techniques, combined beams, treatment planning, new technology, etc. continues to increase the potential benefits. Lastly, dosimetry audits have provided a general environment and example of audit in RT that has led to the broader acceptance and development of audit concepts and methods that have been applied much more widely to RT processes and their quality improvement.

Conclusion

Overall, dosimetry audits have improved consistency in RT results and outcomes for patients and provided confidence to clinicians in the dosimetry supporting their practice. Their importance and impact are clearly recognized and their encouragement of, and links to, other wider radiotherapy audit has been significant. The IAEA's 50-year old programme has been a leader in this. The increasing breadth of uptake of audits is to be encouraged, to include more centres. As the complexity of RT continues to develop, the scope of what can be included in dosimetry and wider RT quality audits also needs to continue to increase.

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Harmonizing quality assurance for radiotherapy in clinical trials: the global group

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Many national and international clinical trials involving radiotherapy are conducted worldwide. There is a growing need for collaboration between different groups conducting these trials for several reasons. Firstly, for

rare diseases or highly specific studies, international cooperation is often required for sufficient patient accrual to achieve adequate statistical significance. Expanding the patient population to a global catchment area can provide a selection of patients within a narrower band of genomic subtypes or other conditions of interest. Secondly, broader acceptance of the trial results, and thus the impact of the trial, can be achieved.

A universal component of multi-institutional radiotherapy clinical trials is quality assurance: these are processes that evaluate whether institutions are capable of following the protocol in a uniform manner. This uniformity achieved through trial quality assurance (QA) results in stronger statistical power of the trial results [1-3]. However, approaches to radiotherapy QA for multi-institutional clinical trials have been developed independently throughout different regions of the world, leading to different types and implementations of QA. If these efforts are harmonized, international collaboration of clinical trials can be streamlined and held to a consistent standard.

The goal of the Global Harmonization Group for Quality Assurance in Clinical trials (GHG) is to promote harmonization of radiotherapy quality assurance between trial groups globally [4]. The group aims to bring together, homogenize and distribute information regarding quality assurance of radiation therapy in clinical trials. We do this by providing a platform for prospective discussions on new audit approaches, software tools, guidelines and policies of trial groups. We are also developing a framework to endorse existing and future radiotherapy quality assurance and guidelines between various trial groups. Each organization will be able to specify which quality assurance procedures from other organizations they endorse and thus accept for future collaborative trials.

The current members of the group are the European Organization on Research and Treatment of Cancer (EORTC), the Imaging and Radiation Oncology Core

(IROC), the Japan Clinical Oncology Group (JCOG), the UK Radiotherapy Trials QA Group (RTTQA) and the Trans-Tasman Radiation Oncology Group (TROG), and the Canadian Cancer Trials Group (CCTG). The European Society for Therapeutic Radiation & Oncology (ESTRO), the International Atomic Energy Agency (IAEA) the Australian Clinical Dosimetry Service (ACDS), the National Physical Laboratory (NPL) and Radiation Dosimetry Services (RDS) are observers.

We aim to promote global harmonization of clinical trial QA within the radiotherapy community by organizing symposia and forums during international scientific meetings, especially recognizing the different approaches to routine radiotherapy (including local QA). We are working to derive a model for validation/acceptance of national and regional basic dosimetry audits for use in clinical trial QA and define clear definitions for higher radiotherapy QA levels that can be used globally [5]. A further aim is to promote research to understand the relative prognostic values, as well as the technical and human resource costs of radiotherapy QA (RTQA) approaches to enable the selection of appropriate clinical trial RTQA requirements, especially those involving advanced technologies. Specific projects undertaken by the GHG include dosimetry audit intercomparison [6, 7], QA for proton trials, harmonization of delineation for organs at risk, and recommendations for the use of dose-to-water and dose-to-medium algorithms.



Members of the Global Harmonization Groups for Quality Assurance in Clinical Trials working together to inter-compare dosimetry audit techniques.

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ESTRO identifies dosimetry audit as key component in achieving high quality radiotherapy

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Dosimetry audits are a key component in quality management programmes in radiotherapy, playing an

important role in the safe implementation of new treatment modalities and techniques [1-4]. National and large scale audits provide data which can help create, sustain and increase standards as well as have the potential to identify issues which may cause harm to patients, thus improving both quality and safety of treatment [1, 4-8]. They can also help to reduce variability in dose delivered to the patient both nationally, internationally and within multi-institutional trials [3, 7-10]. At an institutional level, an external dosimetry audit provides an independent check of the local approaches and thus supports the implementation of novel and complex techniques [6-9, 11-14]. Where multiple centres have been included in the audit, the process of comparison with other centres facilitates awareness and understanding of issues which may exist and which may not be identified by a single centre alone [5-7]. Furthermore, this sharing of experiences allows for the benchmarking of centres with similar equipment and thus increases the knowledge of what is achievable with a particular combination of equipment [15].

Dosimetry audits have been identified in the ESTRO physics strategy as being a topic of high importance which can support quality improvements through the standardization of radiotherapy practice across Europe. Two workshops were held during 2017 to address this subject to identify how existing groups, including the IAEA and clinical trials QA

groups, can work together to develop methods to address specific issues as well as to encourage new national groups to start running local or national dosimetry audits. A combined body of data from dosimetry audits was published in a special issue of *phiRO* [7] and represents an opportunity to share protocols and best practice, with examples of how to start an audit system, thus augmenting the potential for increased quality of radiotherapy. Furthermore, the dosimetry audit data can be combined to create datasets for meta-analysis which can identify issues for investigation into beam modelling and measurement methodologies which require further research, which would not be seen in smaller studies.

Future challenges in dosimetry audits will include technologies such as ion beam therapy and image guided therapy. These audits will demand developments in suitable phantoms as well as a full understanding of the behaviour of the appropriate detectors. Reducing the cost and making audits available for all centres implementing advanced techniques is one of the major challenges in the near future. Creative thinking on how to fulfil the need including techniques such as remote and virtual audits [7] will have to be developed. For a regional/national basis, specific training on how to set up dosimetry audits should be promoted by international organizations such as the IAEA and ESTRO. For these regional approaches, an European network to share phantoms and methodology would be very useful. The ESTRO physics committee remains focused on creating support for both development and dissemination of dosimetry audits.

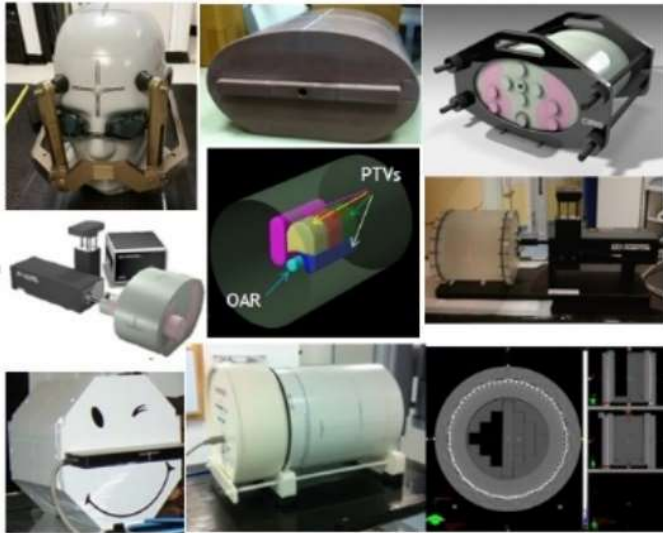


Fig. 1. Various dosimetry audit systems.

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50 years of the IAEA/WHO postal dose audits for radiotherapy

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Historical developments

In the late 1950's the IAEA initiated developing a dosimetry programme and setting up a dosimetry laboratory to, *inter alia*, 'make inter-comparisons of dose measurements' [1]. In

1961 the IAEA's Dosimetry Laboratory was established and its first tasks were: to design an absorbed dose calorimeter, and to prepare and test a system suitable for a postal dose comparison service. Through 1960's the IAEA calorimeter was used for on-site dosimetry comparisons of radiation

beams generated by betatrons at the various centres in Austria, Switzerland, Germany, UK, Belgium and France. The first trial postal dose comparison was organized by the IAEA in 1965 for electron beams using the Fricke dosimeter. In 1966, the IAEA started more systematic investigations in order to develop the methodology for dose comparisons among radiotherapy clinics. Both the Fricke dosimeter and thermoluminescence dosimeter (TLD) were considered suitable for the purpose and, finally, the TLD was selected as it was inexpensive and easy to mail. Following the very first TLD test run with a few advanced clinics in 1966, three larger-scale TLD pilot comparisons were organized, involving about 50 radiotherapy centres in 13 countries. Later in 1967, a panel of experts in medical radiation dosimetry met in Vienna and provided recommendations for the regular operation of the TLD comparison service.

WHO joined the IAEA TLD dose audit project in 1968. The project received its first official name ‘Joint IAEA/ WHO Dose Inter-comparison Service for Radiotherapy’ which evolved to ‘the IAEA/WHO postal dose audit service for radiotherapy’ that is currently in use. In 1969 the TLD Batch #1 of the new postal dose audit service was first documented in the IAEA database.

Initially, the audit service was used for verifying the calibration of ^{60}Co units. Since 1991, high-energy photon beams generated by medical accelerators have been included. Currently, most beams checked are from medical linacs (see Fig. 1).

Over the 50 years of its existence, the IAEA/WHO postal dose audit service has undergone several scientific reviews, technical improvements and various developments leading to better organization and efficiency. Implementation of automatic TLD readers and related IT developments in 1998 allowed to increase the number of beams monitored from 100–150 per year before the automation to 300–400 per year afterwards (Fig. 1). Nevertheless, the requests by radiotherapy centres have steadily grown and recently they are for 700–800 beam audits per year. Several new IT developments took place to ensure smooth operation of the increased volume of the audit service, and timely data processing and handling. The regular follow-up procedure of poor audit results was introduced in 1996 [2]. This is an important component of the service that results in improvements in dosimetry practices in participating hospitals. Local medical physicists are contacted by the IAEA for any dose discrepancies as recorded in audits. When necessary, contacts with local experts in medical physics are made, or international experts are recruited to assist resolving discrepancies at these hospitals.

In addition to auditing hospital beam calibrations, since 1981, TLD audits have been used to monitor the consistency of dosimetry practices at SSDs [3]. In 2017, the IAEA Dosimetry Laboratory phased out its aging TLD systems and upgraded the lab equipment by acquiring new radiophotoluminescence dosimetry (RPLD) systems using glass dosimeters [4].

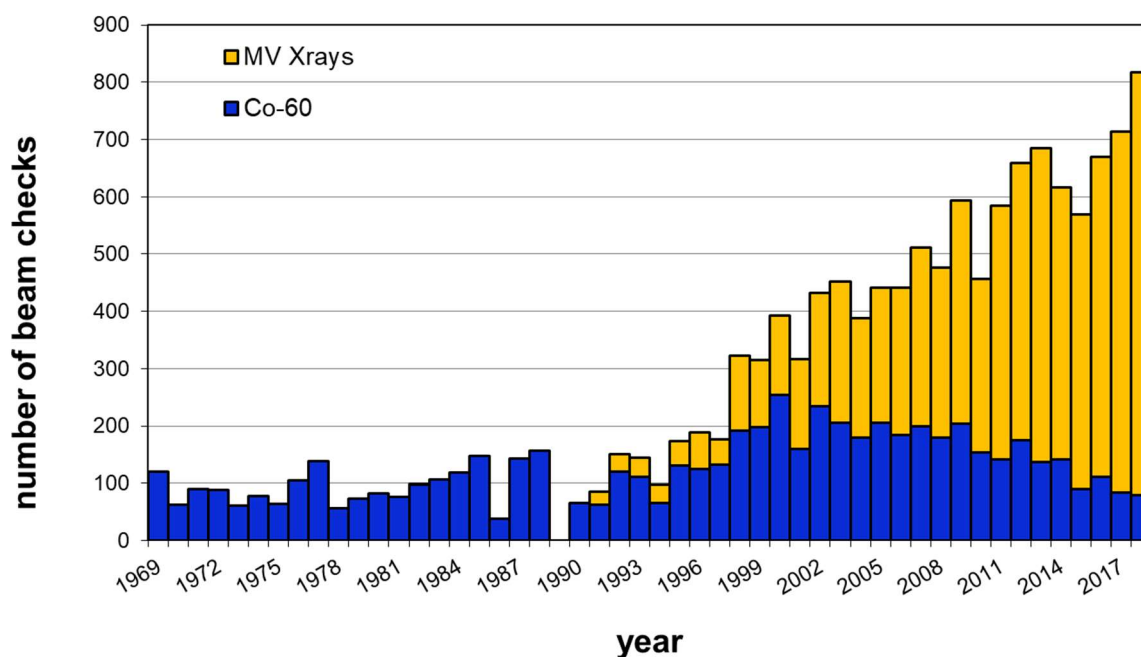


Fig.1. Number of the IAEA/WHO dose audits per year in 1969–2018; Co-60 beams — blue, megavoltage X rays — orange.

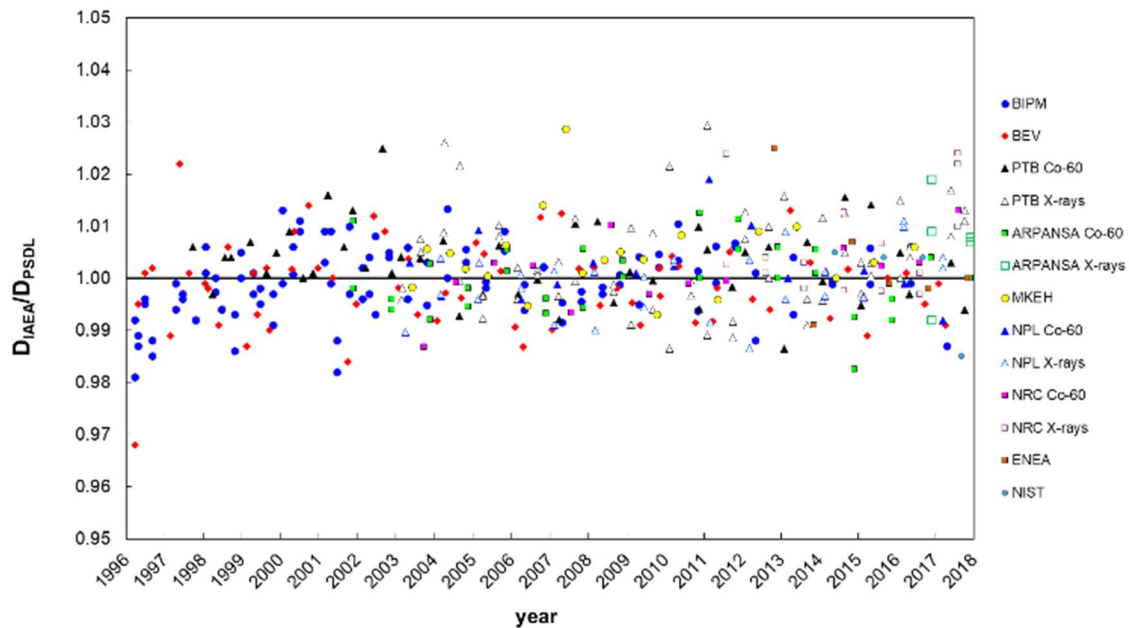


Fig. 2. The results of 428 reference irradiations provided by BIPM and eight PSDLs during 1996–2018. The mean of the distribution is 1.001 and the standard deviation is 0.8% with all data falling between 0.968 and 1.029.

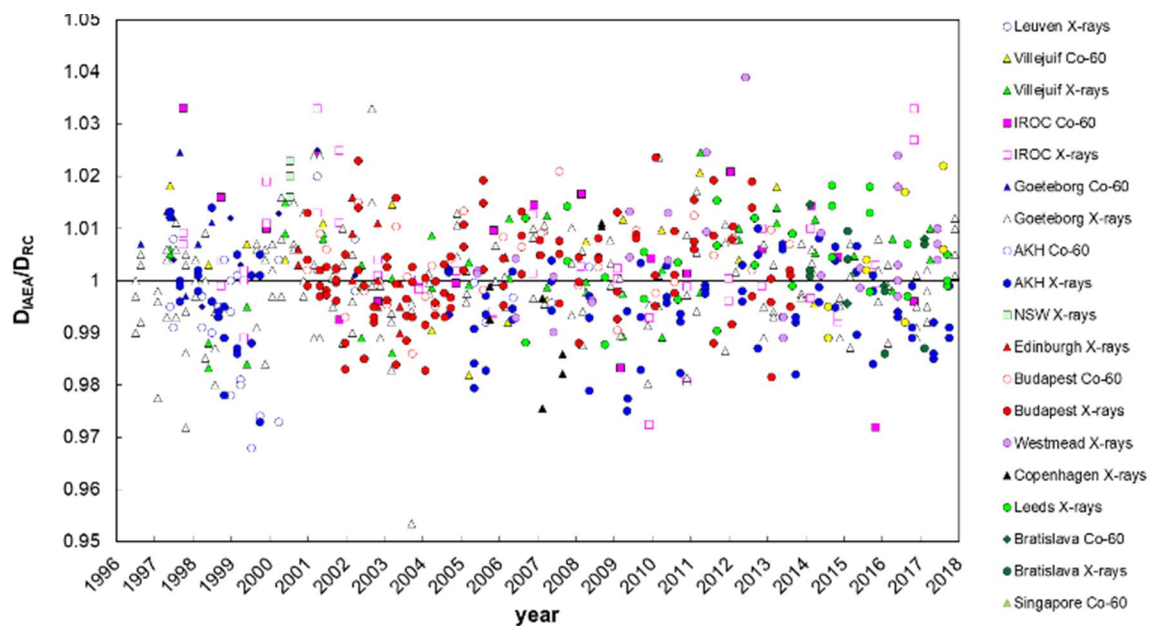


Fig. 3. The results of 740 reference irradiations provided by major DANs and academic radiotherapy centres during 1996–2018. The mean of the distribution is 1.000 and the standard deviation is 1.0% with all data falling between 0.953 and 1.039.

Quality Assurance of the IAEA TLD/RPLD systems

A thorough set of quality assurance (QA) procedures has been maintained for the IAEA TLD/RPLD systems [5]. One important activity is the external verification of the accuracy and reliability of the IAEA TLD/RPLD systems. It is done through regular reference irradiations of IAEA dosimeters by BIPM and several PSDLs, as well as major dose audit networks (DANs) and a few academic radiotherapy centres.

The results obtained since 1996 are given in Fig. 2 and Fig. 3.

Results of dose audits of radiotherapy centres

Over a period of 50 years, the IAEA/WHO service has provided approximately 13 600 dose audits of photon beams from about 4400 radiotherapy units in over 2300 hospitals in 135 countries. The audits were done in low- and middle-

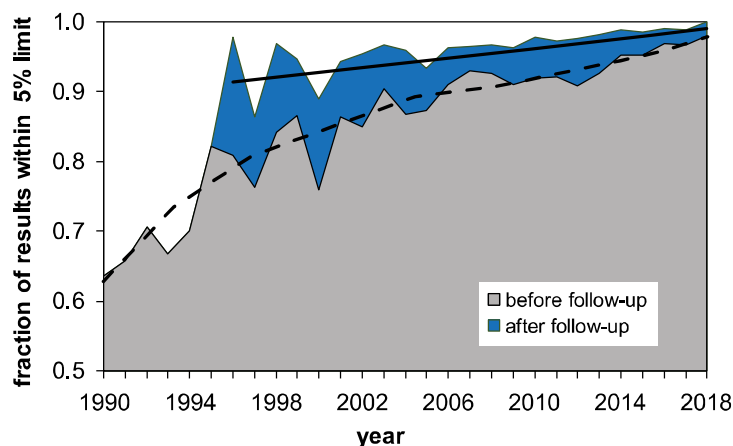


Fig. 4. Fraction of the TLD/RPLD results within the 5% acceptance limit of radiotherapy centres. The grey area indicates the results obtained in the first check, and the blue area corresponds to the percentage of results improved in the follow-up process.

income countries of Africa, the eastern Mediterranean, Europe, Latin America and the Caribbean, Southeast Asia and the Western Pacific. About 80 hospitals per year newly register to the audit service.

In 1969–2018, on average 86% audit results were within the 5% acceptance limit but the IAEA records show a systematic increase in accurate beam calibrations in participating centres from approximately 50% in the early years of the service, 65–70% in early 1990's, to 96–97% at present (see Fig. 4). After the regular follow-up of poor results involving the repeat dosimeter irradiation, the fraction of acceptable results further increased to approximately 99% (Fig. 4). The overall improvement is mainly attributed to the scientific progress and technical developments in dosimetry, increased interest in quality assurance in radiotherapy centres and also because of their regular participation in audits. Hospitals that have systematically participated in the IAEA/WHO audits achieve better results than newcomers to the service. In the last 10 years, 88% results of first-time participants were acceptable compared to 96% acceptable results of regular participants.

It was observed that in general, dosimetry of linac beams was better than that of ^{60}Co beams (Table 1). In particular, poor technical condition of some ^{60}Co units caused by machine age and inadequate maintenance contributed to performance deficiencies and inferior audit results. For example, over 40% of ^{60}Co machines in Eastern Europe and Northern Asia are older than 20 years and approximately 20% are older than 30 years [6]. For a group of ^{60}Co machines over 30 years old the agreement between the measured and stated doses was as low as 70% whereas for younger than 10 years the agreement was over 90%.

TABLE 1. RESULTS OF TLD/RPLD AUDITS IN 2008–2018.

| | Co-60 beams (1510) | High-energy X ray beams (5190) |
|----------------------------------|-----------------------|-----------------------------------|
| Deviations outside the 5% limit: | 12% | 4% |
| > 20% | 3% | 1% |
| 10-20% | 3% | 1% |
| 5-10% | 6% | 2% |
| Results within the 5% limit | 88% | 96% |

Multi-machine radiotherapy centres generally performed better than single machine institutions. This may be related to a more substantial medical physics infrastructure in larger centres.

The information that participants provide in the TLD/RPLD data sheets is systematically analyzed by the IAEA. This is done in order to evaluate the status of calibration dosimetry, to trace the source of any discrepancies in the dose measurement and calculation, and to gain understanding of the use of dosimetry equipment and codes of practice in participating centres. The most common reasons of dose discrepancies pertained to using an incorrect geometry set up for TLD/RPLD irradiation, miscalculation of the absorbed dose or a combination of various mistakes and errors. Special educational material has been developed by the IAEA to aid the participating hospitals in following the specific TLD/RPLD irradiation geometry and dosimetric calculations. This resulted in a decrease in the number of trivial mistakes by about 50%.

The clinical relevance of discrepancies in dosimetry detected in the audit programme was confirmed in several cases [7], and without participation in independent dose audits such discrepancies may have not been discovered. It is of importance for any radiotherapy hospital to be alerted of the dose discrepancy before patients suffer the consequences of undiscovered mistakes.

Dosimetry audits for SSDLs

The IAEA/WHO postal dose quality audit service has monitored the performance of SSDLs in the therapy dose range since 1981. In 1999, postal audits were expanded to radiation protection level dosimetry. Initially, both audit programmes for SSDLs used TLDs. Recently, radiotherapy level audits are performed using RPLDs and the radiation protection audits use optically stimulated luminescent dosimeters (OSLDs). The results of audits for 80 laboratories providing therapy level calibrations in 1997-2018 are given in Fig. 6. The mean of the results' distribution is 1.005 and the standard deviation is 2.2%.

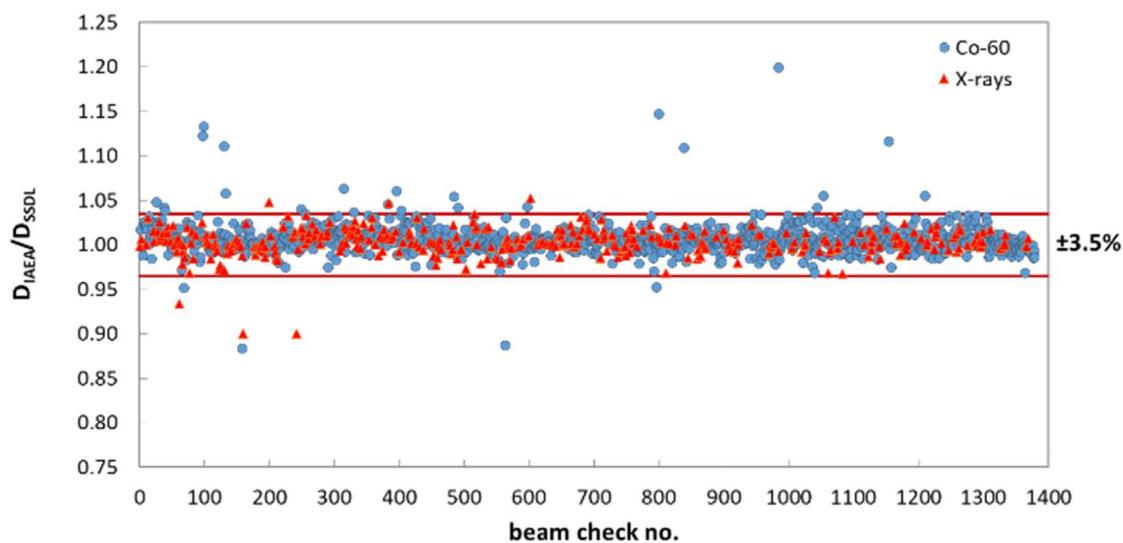


Fig. 5. Results of the IAEA/WHO TLD/RPLD batches 1997–2018. A total of 1379 beam calibrations were checked in 80 SSDLs, which included 1007 ^{60}Co (circles) and 372 high energy X ray beams (triangles); 34 deviations outside the 3.5% acceptance limit were detected.

Approximately 98% SSDL results were within the acceptance limit of 3.5% in this period. The laboratories with deficient results are informed about their discrepancies and assisted to understand and resolve them. A repeat dosimeter irradiation is performed. Typically, all discrepancies in SSDL audits are explained and corrected.

Conclusion

Over the 50 years of its existence, the IAEA/WHO postal dose audit service has played an important role in improving the accuracy and consistency of dosimetry in radiation therapy across the globe. The service has been used by over 2300 radiotherapy hospitals in 135 countries and several clinically relevant errors in the calibration of therapy beams were detected and corrected. By providing dose audits, the IAEA/WHO assist radiotherapy hospitals in achieving and maintaining accurate dosimetry for radiotherapy which benefit many patients worldwide.

Acknowledgements

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thousands of incoming data sheets and discussed with audit participants their dosimetry practices.

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WHO staff is acknowledged for their cooperation and support. Former and present PAHO staff: G. Hanson, C. Borrás and P. Jimenez deserve special mention for their active involvement in dosimetry audits in Latin America and the Caribbean.

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IAEA support to dosimetry audit networks

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Developing audit methodologies: from simple to complex

For over 20 years, the IAEA has encouraged and supported the development and implementation of national activities for dosimetry audits in radiotherapy [1-5]. One of the reasons has been to improve the availability of dosimetry audits for hospitals, in particular those in low- and middle-income countries. A series of four Co-ordinated Research Projects (CRPs) have been conducted by the IAEA in 1995–2017 to assist in developing national audit programmes, primarily using TLDs. This way the IAEA supported the development of methodologies and helped establish several dosimetry audit networks (DANs).

The CRPs introduced nine audit steps gradually increasing in complexity, so that the experience of previous steps was used for the development of subsequent audits. Methodologies for each step were developed in a series of consultants' meetings employing international experts in radiotherapy dosimetry and auditing. Research related to the physical characteristics of the dose measuring systems, development of new phantoms, and feasibility studies for measuring new dosimetry parameters were conducted by the IAEA Dosimetry Laboratory in cooperation with the Medical University of Vienna and the General Hospital, Vienna. Following the feasibility studies, multicentre pilots

involving experts associated with the CRPs and the national DANs were run by the IAEA Dosimetry Laboratory. Then, the methodologies and phantoms were transferred to the national levels for developments and testing of methodological and operational aspects of new audits by the participating DANs. In addition, the IAEA Dosimetry Laboratory contributed to strengthening QA of the national dosimetry systems by exchanging dosimeters and verifying the work of the national EAGs.

Overview of IAEA CRPs on dosimetry audits

The first CRP, "Development of a Quality Assurance Programme for Radiation Therapy Dosimetry in Developing Countries", was conducted in 1995–2000. The aim of the CRP was to disseminate the IAEA TLD methodology for dosimetry audits in reference conditions and provide guidelines for operation of the national QA networks in participating countries. Twelve countries were involved at different stages in the CRP: Algeria, Argentina, China, Colombia, Cuba, the Czech Republic, India, Israel, Malaysia, the Philippines, Poland and Viet Nam. The participants set up their TLD systems with technical support from the IAEA Dosimetry Laboratory, which provided an external quality control of the performance of their national TLD systems. Then, initial TLD trial runs were conducted at the national level with a few selected hospitals to test the

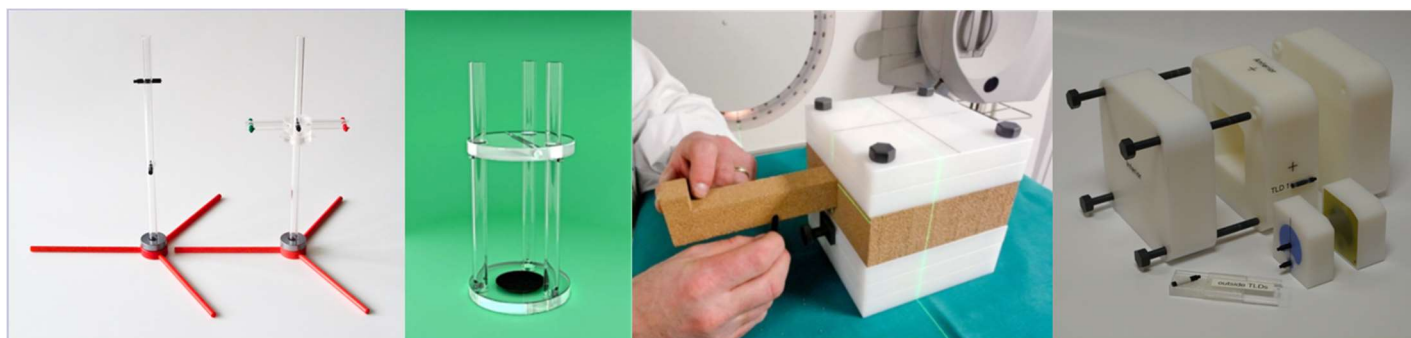


Fig. 1. The TLD holders and phantoms used in the IAEA CRPs; from left to right: holders for dosimetry audits of photon beams in the reference and non-reference conditions, a holder for audit of electron beams, a solid phantom for dosimetry audits in heterogeneity situations, a phantom for IMRT end-to-end audits.

audit methodology, instructions and data sheets and, later, the regular audit programmes were launched at national scales.

Following the completion of the initial CRP, the IAEA continued the previous developments by conducting a second project “Development of TLD-Based Quality Audits for Radiotherapy Dosimetry in Non-Reference Conditions” in 2001–2007. The objective of this CRP was to extend the scope of DAN activities from the basic TLD beam output check to more complex audit measurements in several clinically relevant irradiation geometries including auditing electron beams. The participants of the second CRP were the national DANs of Algeria, Argentina, Bulgaria, Cuba, China, India and Poland.

A further development continued through the third CRP “Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques” conducted from 2009 to 2011, as an extension of the audit steps previously developed and tested. Auditing procedures were developed for dosimetry of more complex irradiation techniques including irregular fields shaped with multileaf collimators (MLC), heterogeneous situations and small MLC shaped fields relevant to stereotactic radiosurgery and intensity modulated radiotherapy (IMRT). The audit programme included both TLD and film-based 2D dosimetry methodology for testing dose distributions in small field geometry. The national DANs participating in this CRP were: Algeria, Argentina, Brazil, China, Czech Republic and Poland.

The fourth CRP “Development of Quality Audits for Advanced Technology in Radiotherapy Dose Delivery” was conducted in 2013–2017. It included an audit of TPS calculation of small field output factors and film dosimetry audit of MLC positional performance for IMRT, TLD and film audit of single clinical IMRT field dose delivery and ‘end-to-end’ audit (imaging, treatment planning, and dose delivery) for multiple field IMRT techniques using TLD and films. The national DANs involved in this CRP were those of Algeria, Brazil, China, Czech Republic, India, Poland and Thailand.

The detailed description of the methods, instructions, data sheets and result reporting forms which were developed and tested through these CRPs are shared with the broader community through the IAEA DAN database [6]. Examples of TLD holders and phantoms used in the CRPs are shown in Figure 1.

DAN database

The IAEA has developed a database describing the activities of dosimetry audit networks operating in the various world regions. The purpose was to inform the radiotherapy physics community of the availability of dosimetry audit programmes in their countries or regions, and to share information with the auditing organizations, which could compare their activities and exchange experiences. The

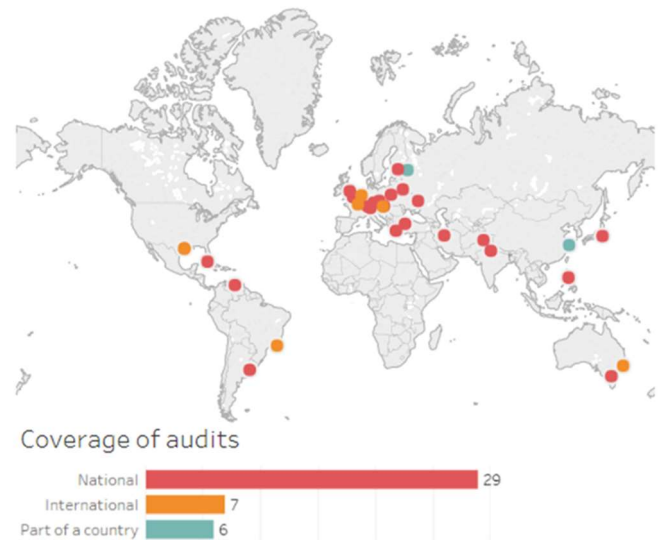


Fig. 2. Status of active Dosimetry Audit Networks in 2017.

initial IAEA questionnaire asking for information on audit programmes was sent in 2010 to over 80 institutions, mostly members of the IAEA/WHO SSDL Network and other organizations known for having run dosimetry audits for radiotherapy in their countries or internationally. Since then, data have been collected through regular surveys to populate the database. In 2017, 45 organizations in 39 countries confirmed they operate dosimetry audit services for radiotherapy (Figure 2).

The information available through the DAN database suggests that the current capabilities of the dosimetry audit networks operating in various world regions are insufficient to adequately serve radiotherapy centres and further efforts should be made to improve availability of dosimetry audits [7].

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Two decades of audit methodologies development: from a reference point to 3D audits

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The collaboration between the Medical Radiation Physics group at the Department of Radiation Oncology, Medical University of Vienna/AKH Wien and the IAEA Dosimetry Lab for the development of audit methodologies was initiated in 1999. The success of this collaboration between medical physicists from the IAEA and the Medical University of

Vienna and their commitment was mostly based on the common understanding that successful radiotherapy treatment needs high quality dose delivery and thus medical physics input and training. Obviously, the concentration of complementary medical physics and dosimetry expertise from both groups located in Vienna ever called for a more intensive collaboration. This was also facilitated by a history of previous interactions within the international scientific community.

I have had the great pleasure to contribute as a consultant to the development of audit methodologies for two decades, serving in several coordinated research projects (CRP). Within this time span radiotherapy has seen an enormous technological hardware and software progress that improved dose delivery as well dose calculation and treatment plan optimization. The sequence of CRPs was well synchronized with all these developments and the resulting needs in radiotherapy, starting with audits devoted to beam calibration down to audits that were versatile enough to validate calibration of a high-end multileaf collimator, to check basic input data of state-of-the-art treatment planning systems for high precision radiotherapy techniques involving small fields, or to check complex inversely planned intensity modulated radiotherapy (IMRT) delivery

including volumetric arc therapy (VMAT) with multidimensional dosimetric methods.

The evolution of dose delivery techniques of the last two decades obviously necessitated expanding the dosimetric methods at the IAEA Dosimetry Lab. Such an extension of methodologies is a huge challenge, but was required to serve the IAEA Member States by running audits; and furthermore, to be rolled out to SSDLs and Dosimetry Audit Networks (DAN) in other countries so that they can run audits for advanced treatment techniques. Applying film dosimetry necessitated more extensive methodological developments of dosimetric procedure including phantom developments, subsequent feasibility studies and pilot testing, respectively. My team and me ever enjoyed our given tasks in the CRPs, ranging from initiating them in consultant meetings to the determination of specific correction factors of dosimetric setting. It was always the practical aspects of dosimetric audit developments that were most appealing. The mimicking of real treatment conditions when running feasibility studies and pilot testing at our radiotherapy department took many evenings and weekends; it was a sequence of irradiation sessions of collaborative efforts between staff members of the Medical University of Vienna and the IAEA, but it never felt like a burden. Instead, it was deepening the relation of staff members beyond a pure professional level.

Last but not least, being involved in a CRP implies collaboration beyond the borders. Sharing professional experiences with CRP participants and other consultants from various countries all over the world, meeting and discussing with them about radiotherapy, medical physics and about topics beyond our profession was an experience I do not want to miss. It was the great opportunity for my team to collaborate and contribute to the development of audit methodologies to the ultimate benefit of cancer patients treated with radiation across the globe.

The Radiological Physics Center and Imaging and Radiation Oncology Core Houston QA Center's 50 years of vigilance and quality assurance for the radiation oncology community worldwide

D. S. Followill

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In 1968, the Committee for Radiation Studies (CRTS) at the National Cancer Institute (NCI) recognized the need for consistency in the delivered radiation dose to clinical trial patients. The Radiological Physics Center (RPC) grant was originally awarded through a competition sponsored by the AAPM. The grant announcement called for the establishment of a center of operations for the implementation of this scientific program, in other words, the creation of a Radiological Physics Center. Thus, MD Anderson won the competition and the RPC was established in 1968 to contribute to the development, conduct, and QA of multi-institutional cooperative group clinical trials. One key aspect to the RPC's function is that it operates as an independent quality assurance office for multi-institutional cooperative group clinical trials. Its mission was and continues to be to assure both the NCI and clinical cooperative system that institutions participating in the clinical trials process deliver comparable and consistent radiation therapy.

In 2014, the NCI reorganized its clinical trial program to create a more efficient and cooperative network of clinical trial groups. As part of that reorganization, the radiation therapy and imaging clinical trial QA centers combined to form the Imaging and Radiation Oncology Core (IROC) cooperative. The RPC was renamed the IROC Houston QA Center (IROC-H). IROC-H's mission remained the same as before and continued to administer its QA program to trial participants worldwide. The RPC/IROC-H QA Center has been funded continuously since 1968 under Dr. Robert Shalek's guidance (1968-1985), followed by Dr. William Hanson (1985-2001), Dr. Geoffrey Ibbott (2001-2010) and currently by Dr. David Followill (2010-present). See Figure 1.

The RPC/IROC-H QA Center currently monitors 2,214 institutions, with over 4,400 therapy machines, which participate in cooperative group clinical trials sponsored by the NCI, other National Institute of Health trials, EORTC trials and pharmaceutical company trials. These institutions are located primarily in the USA and Canada, but also include 365 participants from 52 other countries.

The five major components of the RPC/IROC-H's QA program are: 1) the remote TLD/OSLD audit of machine

calibration, 2) on-site dosimetry review visits, 3) credentialing for advanced technology clinical trials, 4) review of patient treatment records and approval/credentialing of proton therapy institutions.

Remote audits of machine output calibration

The RPC/IROC-H initiated its TLD output verification program for photon beams in 1977. In 1982 electron beams were included, and in 2007, the verification of proton beam outputs began. A key change to this program occurred in 2010 with the replacement of TLD with Optically Stimulated Luminescent Dosimeters (OSLD) for the vast majority of its beam audits. RPC/IROC-H, in 2018, measured nearly 18,250 beams worldwide.

The RPC/IROC-H's machine output program is notable for its simplicity. On an annual basis, institutions receive a package with acrylic mini-phantoms containing several TLD capsules (for protons) or OSLDs (for photons and electrons). When the TLD/OSLD measurement disagrees with an



Dr. Shalek 1968-1985



Dr. Hanson 1985-2001



Dr. Ibbott (2001 – 2010)



Dr. Followill (2010 – present)

Fig. 1: The four RPC/IROC-H Directors.

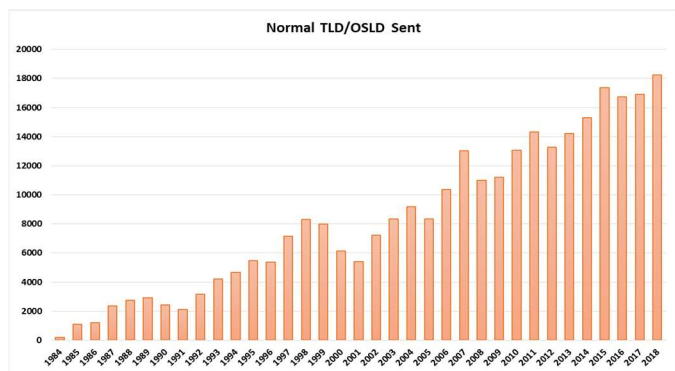


Fig. 2. The number of beams audited per year since 1984.

institution's stated dose by more than 5%, the RPC/IROC-H initiates a series of activities to resolve the discrepancy. To date, over the past 50 years, we have monitored a total of 311,769 therapy beams. The growth in this monitoring program since 1984 is shown in Figure 2.

On-site dosimetry review visits

The RPC/IROC-H conducted its first on-site audit in 1968 and has since, made 2,543 site visits to 849 institutions. The RPC/IROC-H visit procedure consists of a review of the institution's QA procedures and documentation; a review of treatment records, assessment of IGRT capability and dosimetry measurements of the radioactive sources and radiation beams. Key recommendations from 409 site visits are shown in Table 1. A substantial percentage of institutions still have errors in their QA program as identified by the site visits.

TABLE 1. TYPE OF ERROR AND FREQUENCY OF ERRORS FOUND DURING RPC/IROC-H'S 409 INDEPENDENT SITE VISIT REVIEWS.

| Errors Regarding | Number of institutions (%) |
|---------------------------|----------------------------|
| Review of QA program | 337 (82) |
| small field output factor | 132 (59) |
| wedge factor | 134 (33) |
| off-axis factor | 87 (21) |
| electron calibration | 83 (20) |
| photon depth dose | 75 (18) |
| Electron depth dose | 70 (17) |
| Temp/Pressure correction | 44 (11) |
| Beam symmetry | 34 (8) |
| Photon calibration | 32 (8) |

Reviews of patient treatment records

In some cases, the RPC/IROC-H reviews the treatment plans prepared by participating institutions to ensure that the treatment plans meet the dosimetric requirements of the clinical trial protocol. Over the past 50 years, RPC/IROC-H has reviewed over 18,000 patient treatment records. Nearly 39% of the charts reviewed by the RPC/IROC-H contained

one or more of the errors described above. This is a substantial number that is attributed to mainly human error at the treating institutions. In each case, the error was corrected by the RPC/IROC-H and reported to the study group so that correct information could be used for evaluation of the clinical trial.

Credentialing for advanced technology clinical trials

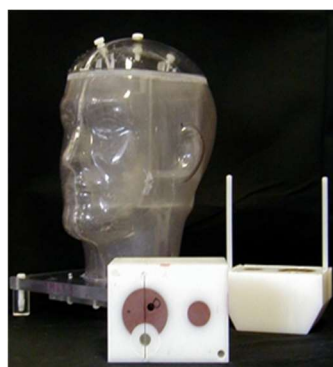


Fig.3. The RPC/IROC-H's H&N phantom.

Clinical trials that require the use of advanced technologies such as IMRT, SBRT, and proton therapy are considered sufficiently challenging to the extent that institutions are required to demonstrate their ability to use these technologies before being permitted to register patients. Credentialing for such

clinical trials generally includes the irradiation of one of the RPC/IROC-H's end-to-end anthropomorphic phantoms. The most common phantom shipped to institutions is the IMRT Head and Neck (H&N) phantom (Figure 3) which has been sent over 2,400 times since 2001. In addition to the H&N phantom, the RPC/IROC-H also has pelvic, thorax, liver, spine, brain phantoms for both photon and proton radiation therapy. The historical mailout of all phantoms worldwide since the credentialing program began is seen in Figure 4. The RPC/IROC-H phantom credentialing program continues to grow as each reaches out to more and more international sites.

Approval and credentialing of proton centers

Proton site visits by the RPC/IROC-H started in 2008 as new proton centers were built and began to enter patients into NCI-funded clinical trials. Institutions interested in participating in clinical trials with proton therapy must first complete five approval steps for each proton delivery method outlined by the NCI. The approval of proton on-site audits allow IROC to review the institution's treatment planning process, from simulation to treatment delivery, as well as their quality assurance practices. The RPC/IROC-H QA Center has conducted 34 proton site visits verifying various different delivery modalities. Currently, 26 of the 31 clinically active proton centers monitored by the RPC/IROC-H (see Figure 5) had one or more treatment delivery modalities approved for use in clinical trials.

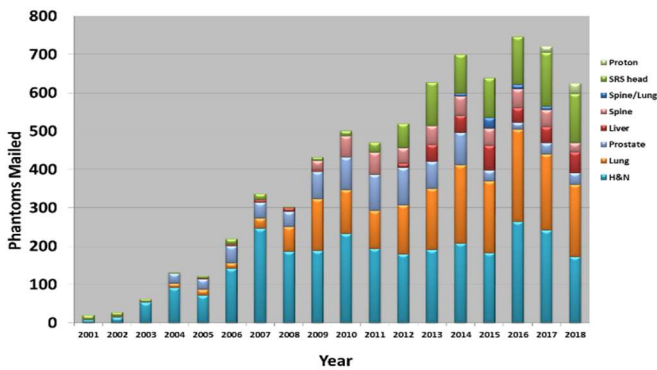


Fig. 4. Number of all RPC/IROC-H phantoms mailed since 2001.

Publications and interaction with the radiation oncology community

One of the aims of the RPC/IROC-H QA Center is to disseminate information and findings to the radiation oncology community. Our staff accomplish this aim through active membership on committees, subcommittees, working groups and task groups of ASTRO, AAPM, ACMP, HPS, and the ACR. Our closest relationship is with the AAPM

where we have co-authored 22 AAPM task group reports establishing medical physics standards. We also conduct research to enhance our ability to provide an optimum service to the study groups and participating institutions to improve patient radiotherapy dosimetry. To this end, we have published a total of 326 peer reviewed manuscripts since 1972 of which 141 were published since 2010 under the guidance of Drs. Ibbott, Kry and Followill.

Conclusion

The majority of institutions audited by the RPC/IROC-H meet the acceptance criteria, however, a large number of institutions fail to meet these criteria. The RPC/IROC-H QA Center endeavors to understand the reasons for such discrepancies, and to educate the institutions in the procedures needed to resolve them. The RPC/IROC-H efforts and findings over the past 50 years suggest that errors continue to manifest in radiotherapy, and without its independent QA program, many of these errors would go undetected. The RPC/IROC-H remains vigilant and ready to assist institutions to improve the accuracy of dose delivery to their patients.

Dosimetry audits for radiotherapy in Argentina

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The SSDL in Argentina was established in 1968 through an agreement between the World Health Organization (WHO) and the National Atomic Energy Commission (CNEA) in cooperation with the International Atomic Energy Agency (IAEA). This SSDL is a member of the IAEA/WHO SSDL Network. The SSDL undertakes the duty of providing the necessary link in the traceability chain of radiation dosimetry to the international measurement system (SI). The SSDL is also responsible for disseminating calibrations at specific radiation qualities appropriate for the use of radiation measuring instruments.

The radiotherapy level calibrations have been carried out by the SSDL since 1970. In 1978 a TLD-based system began to be implemented with the purpose of performing dosimetry audits in reference conditions to verify the calibrations of cobalt 60 radiotherapy beams in hospitals and health services. Over the years, the SSDL participated in a series of Coordinated Research Projects conducted by the IAEA and extended the scope of audit activities to high energy photon beams, as well as to complex audit measurements in a variety of clinically relevant irradiation geometries.

In the frame of the Technical Cooperation (TC) Programme, the IAEA assisted the upgrading of our TLD laboratory. An automatic PTW FIMEL PCL3 reader was installed in 2004 which replaced the old Teledyne Isotopes 7300C reader. A

complete new set of ancillary instruments were also received through this TC project. After the upgrading, routine, TLD postal audits for high energy photon beams in reference and non-reference conditions, on axis and off-axis beam, were resumed. With constant technological growth, TLD based dosimetry audits for irregular MLC fields for conformal radiotherapy were also incorporated into the audit programme.

The TLD audit programme covers approximately 15 cobalt therapy machines and more than 80 linacs in the country. The radiotherapy hospitals and clinics participate voluntarily. This programme has a quarterly periodicity in order to be able to provide a service to all the radiotherapy centers that want to participate. The TLD external audits in reference and non-reference conditions on the beam axis are performed for all beam energies in clinical use and all treatment units in each individual hospital.

After each TLD audit is performed, the dose deviation and the data sheet sent by the participants are analyzed. If the dose deviation is larger than 5%, the causes of discrepancy are investigated. A direct communication with the centers is made if the information given in the data sheet is not sufficient to obtain a conclusion about the reasons for the



Fig. 1. The TLD system used for dosimetry audits in Argentina.



Fig. 2. SSDL staff preparing dosimeters for audit.

discrepancy. If the causes of the discrepancy are not detected and the dose deviation is not larger than 10% the participant is included in the next audit without making any change in the beam dosimetry. If the causes of the discrepancy are not detected and the deviation is larger than 10% the participant is required to recalibrate the machine before being included in the next audit run.

General policies for quality audits have been adopted as follows:

- The external audit is repeated every two years for those radiotherapy centers where no deviation larger than 5% has been detected and, every year for the beam energies and treatment units where deviations larger than 5% have been observed.
- New centers are checked in the reference conditions as a first step of quality auditing;

- If a center changes the source, or a major repair of the machine is performed, or a new machine is installed, it is required to participate in the reference and non-reference conditions on axis audit, depending on the previous results obtained by the center.

- Follow-up TLDs will be sent for re-auditing of those parameters where a large deviation was found.

It is expected that in the next years a greater number of equipment will be added to the audit programme. This will require the implementation of a complementary dosimetric system that will enable a shorter evaluation time. For this purpose, a new dosimetric system based on the use of optically stimulated luminescence (OSL), has been established. This will allow the expansion of the SSDL's dosimetric audit programme.

A brief history of the Australian Clinical Dosimetry Service

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Introducing the ACDS

The Australian Clinical Dosimetry Service (ACDS) is a bespoke solution for a national radiotherapy dosimetric auditing service. The ACDS was designed in 2010 by experts drawn from the three professions; medical physicists, radiation therapists, radiation oncologists, in consultation with the national Department of Health. This paper describes how an initial pilot programme concept

developed into a sustainable functioning audit service, over three distinct phases.

The concept of a national auditing service was nurtured by the professional colleges of Australia, representing the medical physicists, radiation therapists and radiation oncologists, until patient mistreatments associated with dosimetry errors in both Coffs Harbour and Adelaide provided a catalyst for the Australian Health Ministers Advisory Council (AHMAC) to support a federally funded

pilot. In 2009/10 discussions between the Department of Health and the professional advisory groups, informed by the Baume Report [1], crystallised into a Memorandum of Understanding, (MoU) between the Department of Health, who funded the pilot, and the Australian Radiation Protection and Nuclear Safety Agency, (ARPANSA) who hosted it.

2011-2014: Initial free-of-charge pilot

The government-funded pilot phase allowed the ACDS the time to recruit staff, develop the three different levels of audit shown in Table 1, and have sufficient resources to adopt an ISO17025 quality approach. Engagement with the clinical community was crucial during this phase, as well as continuing the engagement with relevant government departments, regulatory bodies and the professional colleges. The number of audits performed each month increased throughout the pilot programme as the procedures were optimised. By the end of the pilot programme, all radiotherapy facilities had received an audit. Approximately four to six staff members were employed during the pilot phase.

2015-2016: Two-year transition moving towards a user-pays approach

At the completion of the pilot programme, there was strong support from the government and professional bodies for the continuation of ACDS. The model of sustainable operation that was supported by AHMAC was a user-pays approach. An additional two years of fully government-funded audits were provided to allow for preparation to move to a user-pays scenario. During this stage, the ACDS moved into an annual audit schedule (Table 1) for all Australian radiotherapy facilities (approximately 100 facilities) on a voluntary basis. The regularly scheduled audits helped to embed the culture of dosimetry auditing and enhance the existing safety culture in the hospitals. The ACDS remained committed to improving the clinical relevance and value of their audits and included Intensity Modulated Radiation Therapy (IMRT) and Volume Modulated Arc Therapy, (VMAT) testing in the higher-level audits. Approximately eight staff members were employed during this transition phase.

2017-2018: Successful transition to sustainable user-pays approach

From 2017 the ACDS was funded solely by subscription fees from radiotherapy facilities. Over the course of 2017 increasing numbers of radiotherapy facilities subscribed to the service until in 2018 all Australian facilities had subscribed. Regulation of radiotherapy facilities is state/territory-based in Australia. Some subscriptions were voluntary, and in some jurisdictions, there were additional regulatory drivers. Staff levels increased during this phase to match the audit workload due to increasing subscriptions.

Eight staff were recruited to provide the audit service to the whole nation.

Location within Australian Radiation Protection and Nuclear Safety Agency

The ACDS is located in ARPANSA, which includes Australia's Primary Standards Dosimetry Laboratory (PSDL) with their Elekta linac. Co-location with the standards laboratory and access to their laboratory, equipment and expertise was vital to the ACDS' success. The PSDL staff provided dosimetry support and advice when designing and commissioning new audits, as well as actively participating in audits when increase in demands required greater capacities. ARPANSA also provided professional support to the ACDS for any financial, legal, computing and administrative issues. The drawback with being located within ARPANSA is the disconnection from the clinical environment. It is imperative to the ACDS to maintain relevance to the clinical practice and be seen to be abreast of the latest advances in the field. This potential risk is mitigated by active recruitment of physicists and radiation therapists from hospitals. Regular work-force rotation means that clinical physicists and radiation therapist within the ACDS have moved back into clinical roles and filling the vacancies has enabled the ACDS to bring fresh clinical perspective to the service. The ACDS also contacts their alumni to function as external auditors once they return to the hospital environment and engages experts in particular areas (eg. Stereotactic body radiation therapy (SBRT)) to assist in design and performing these audits. Additionally, an independent clinical advisory group (CAG) consisting of radiation oncologists, medical physicists and radiation therapists provide the necessary clinical perspective

TABLE 1 ACDS AUDIT STRUCTURE AND FOUR-YEAR SCHEDULE FOR A RADIOTHERAPY FACILITY.

| Year | Level |
|------|--|
| 1 | Level III – onsite end-to-end audit where the anthropomorphic phantom undergoes all steps within the radiotherapy treatment chain. |
| 2 | Level I – mail-out reference dosimetry audit using Optically Stimulated Luminescence Dosimeters (OSLD). |
| 3 | Level II – onsite clinical dosimetry audit testing beam model commissioning where treatment plan fields are measured on 2D array in a simple geometry. . |
| 4 | Level I – the mail-out OSLD audit is performed every second year. |

Social drivers of audits

One of the main reasons for the ACDS' success has been the active awareness and interest of professional colleges, collaboration with government, and the engagement between the PSDL and clinical physicists. The colleges' engagement with dosimetric risk is exemplified by the collaboratively designed National Radiation Oncology Practice Standards which include a minimum dosimetric audit program commensurate with patient safety. Additional social drivers are considered below:

Peer influence: When auditing a facility, especially at the beginning of the pilot, auditees frequently asked whether the neighbouring facility has been audited.

Benchmarking: Auditees frequently asked how they performed relative to the local and national results.

Perceived quality: As the ACDS program progressed and collected more data for each of the audit types, the weight of evidence supporting the ACDS' scoring technique matured. Presenting data analysis publicly and privately impressed upon facilities the quality and reliability of the ACDS program.

Free pilot: When invited, every radiotherapy provider agreed to participate in the audit pilot which was provided at no financial cost to the provider.

Outcomes from ACDS audits

The encompassing justification for a dosimetric audit program is that it improves patient safety and/or the quality of patient treatment. The ACDS' evidence that it is justified in the Australian context is drawn from the recommendations which it has made to clinical providers which have been adopted. The recommendations have ranged from advising dosimeter replacement due to obsolescence or fault, all the way to reviewing dose



Fig. 1. ACDS audit team (photo courtesy of J. Lehmann).

calculation algorithms which led to changes in clinical practice [2, 3]. Over 200 recommendations have been issued to facilities.

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BELdART: A Belgian dosimetry audit programme in radiotherapy based on alanine/EPR and radiochromic film dosimetry

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Introduction

The Nuclear Technology Centre (NuTeC) has been performing external dosimetry audits since 2009 [1] for Belgian radiotherapy departments. The Belgian Federal

Agency for Nuclear Control (FANC) requested a national audit programme for reference and non-reference conditions that led to the creation of the BELdART project. All Belgian centres could participate in the trial free of charge. This was the first large-scale dosimetry audit programme using

alanine/EPR dosimetry. A team of experts in collaboration with the Belgian Hospital Physicists Association (BHPA) acted as the scientific advisory body to BELdART.

Subsequently, BELdART has developed audit programmes for advanced and dynamic radiotherapy (e.g. IMRT, Arc, tomotherapy, stereotaxy) based on alanine/EPR and radiochromic film dosimetry. A steering committee composed of five senior medical physicists functions as the advisory body to BELdART.

History and past activities

In 2009-2011, all Belgian radiotherapy departments were audited for at least one linac. Overall, 61 machines and 212 beams were audited. The audit encompassed an on-site visit by one BELdART employee who performed the mechanical tests and dosimetric verifications together with the local medical physicist. The output of photon and electron beams was verified in reference and non-reference conditions. The difference between the planned and measured doses was within 3 % for 96.7 % of the MV photon beams and 81.6 % of the electron beams. The positive feedback from the participating departments led the Belgian College of Radiation Oncology and the Federal Public Service

Healthcare to launch BELdART-2 within the framework of the national Cancer Plan.

BELdART-2 is a national postal audit programme involving complex radiotherapy techniques. The audit consists of basic tests using alanine detectors in water derived from the previous phase and an 'end-to-end' test to verify the delivery of dynamic radiotherapy for a prostate case using an anthropomorphic phantom loaded with alanine and radiochromic film detectors. All Belgian centres could participate free of charge to the trial during 2012-2016. Twenty-one centres participated with 34 beams. For the

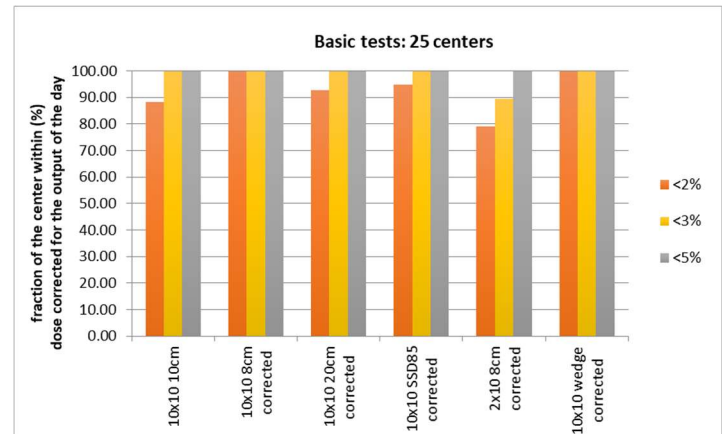


Fig. 1: Results from BLdART-2 (2012–2016).

basic tests, the difference between the measured and planned dose was within 3 % for all centres. For the end-to-end tests, the difference between the planned and the doses measured by EPR was within 3% for 84% of the centres. The film dosimetry results show that 97 % of the centres had a passing rate higher than 95% for the gamma evaluation [2, 3] with the criteria of 3%/3 mm, global gamma, with a threshold of 10%.

The choice of alanine-EPR dosimetry is justified by the low uncertainty that can be achieved, i.e. 1% or less with the technique we use [4, 5]. The measured doses are directly traceable to Physikalisch-Technische Bundesanstalt (PTB), the primary standard laboratory in Germany. The reading of alanine detectors is non-destructive with a very low fading which is invaluable for an audit service. Alanine detectors are also used for the film calibration. The films themselves are analysed using the triple channel dosimetry proposed in [6, 7].

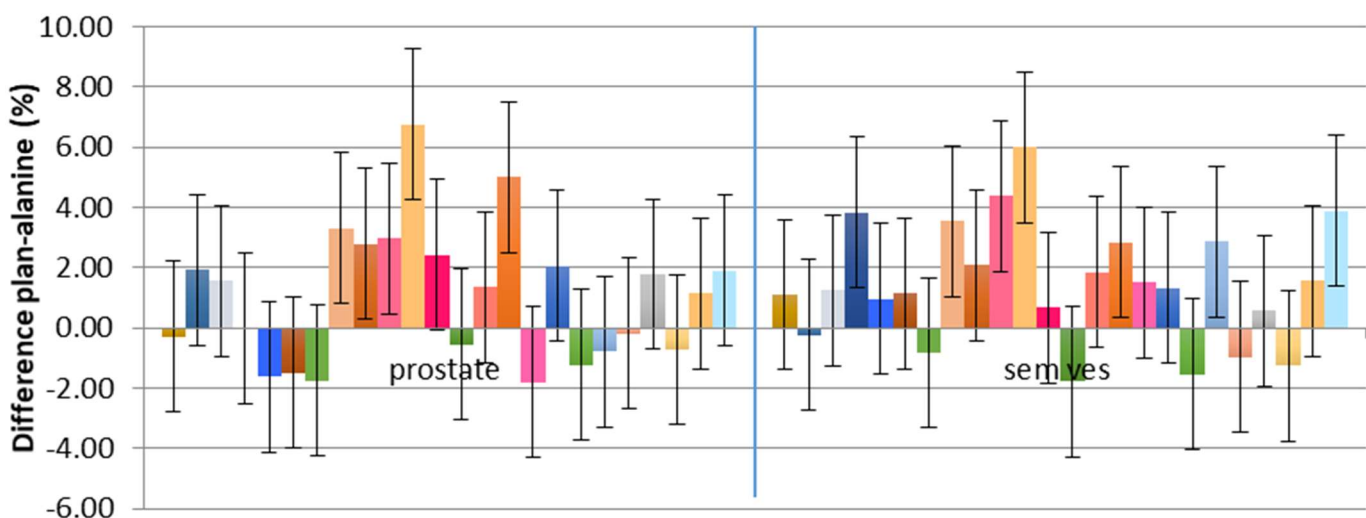


Figure 2: Alanine results from the anthropomorphic phantom in the high dose region. Left: pellets in the prostate, right: pellets in the seminal vesicles

Current activities

BELdART is supported by the Belgian College of Radiation Oncology to continuously develop new audit programmes. Currently BELdART focuses on stereotactic treatments. All Belgian centres can participate free of charge in the intracranial SRS trial. Meanwhile, BELdART is also developing an audit protocol for lung SBRT. Besides, BELdART is still offering postal BELdART-2 audits and basic tests in water based on EPR dosimetry.

Currently, the BELdART staff consists of one physicist, one engineer and one laboratory technician. The BELdART team performs dose measurements in their dosimetry lab in Diepenbeek, Belgium [3]

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TLD postal audits in radiotherapy in Brazil

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The National Cancer Institute (INCA) Quality Program in Radiotherapy (PQRT) started in 1999 as a three-year pilot postal audit program with only 33 radiotherapy services, using the IAEA system for reference conditions. Due to the positive results it has been integrated into the permanent INCA programs and its activities extended to all the radiotherapy services of the country, mainly those where patients from the National Health System (SUS) were treated. Therefore, since 2003 it became a national program, cost-free for all participants, to stimulate and to promote radiotherapy with quality, efficacy and efficiency.

In 2003 we created our own system (Fig. 1), able to measure photon beams in reference and non-reference conditions [1]. It evaluates the following parameters: reference beam output, depth dose at 10 cm and 20 cm, dose to rectangular field, beam quality (for linacs only), wedge and tray transmission factors, dynamic wedge factor and field flatness and symmetry. TLDs are irradiated in a standard water phantom at SSD according to our irradiation protocol. This system has been used in Brazil but also in some countries of Latin America and the Caribbean.

In Brazil, from 2003 till 2018 we evaluated 131 Co-60 machines where 862 tests were performed; and 708 linac beams, where 5445 tests were performed. The main problems that were identified were:

- Co-60 machines: field flatness (12.4%), depth dose at 10 cm (14.0%) and wedge filter factor (15.9%).
- linacs: depth dose at 10 cm and 20 cm (8.6%) and rectangular field dose (7.4%).

In Latin America and the Caribbean, from 2005 till 2018 we evaluated: 48 Co-60 machines where 270 tests were performed and 448 linac beams where 3358 tests were performed. Hospitals from the following countries participated in our audits: Argentina, Bolivia, Chile, Colombia, Costa Rica, Cuba, Ecuador, Guatemala, Honduras, Mexico, Panama, Paraguay, Peru, Dominican Republic, Uruguay and Venezuela. Until now our main partners have been Argentina and Chile. The main problems that were identified were:

- Co-60: depth dose at 10 cm (16.7%); wedge filter factor (15.6%) and field flatness (12.9%);
- linacs: rectangular field dose (9.1%); depth dose at 10 cm and 20 cm (7.3%) and wedge factor (5.7%).

Following our long experience and the improvement of the radiotherapy techniques, this postal photon beams system were updated and after January 2019 it evaluates only: off-axis dose, dose using multi-leaf collimator (MLC) fields, MLC transmission factor, depth dose using FFF and dose for

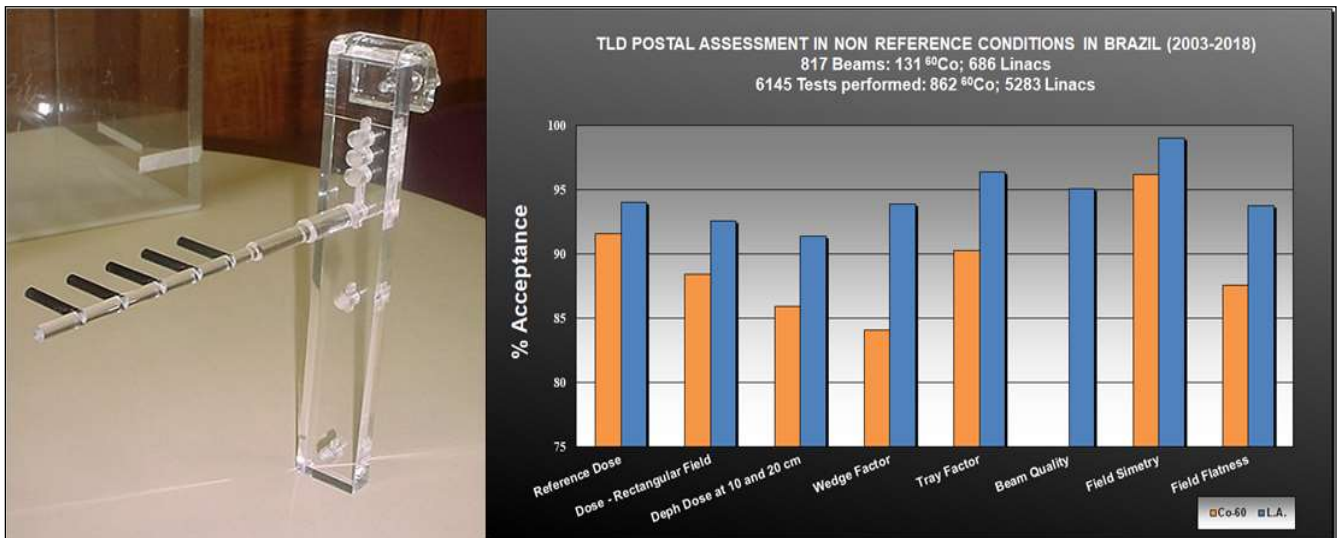


Fig. 1. INCA TLD postal system for photon beams audits and its results in Brazil.

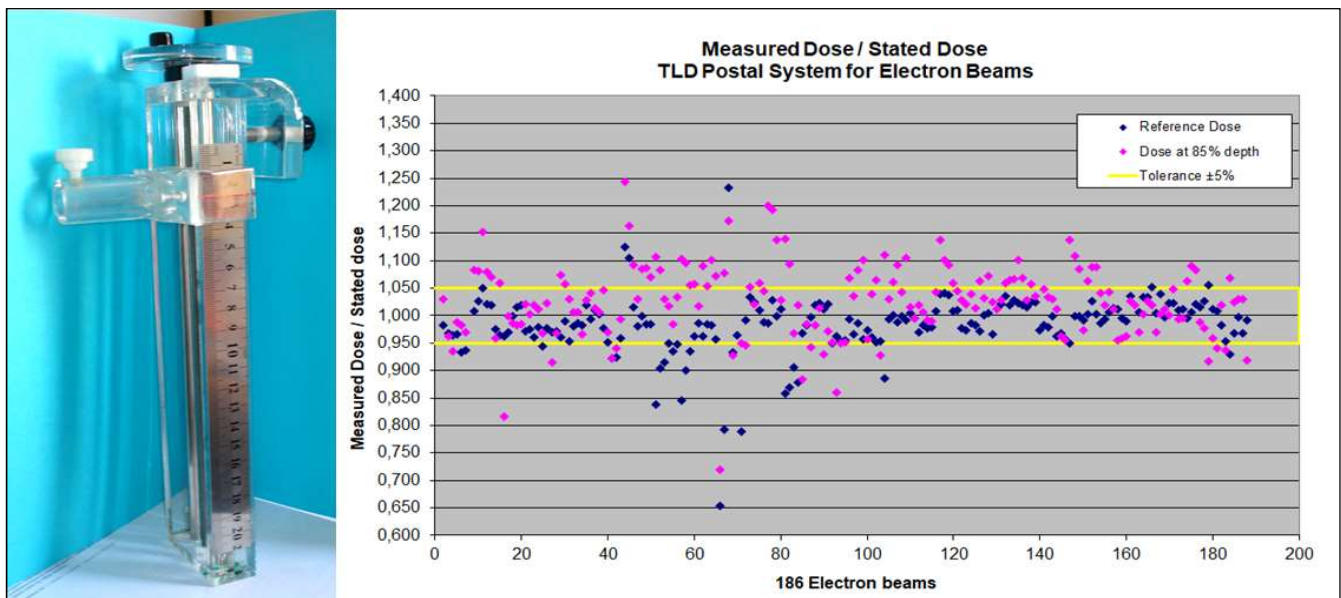


Fig. 2. INCA TLD electron postal system and its results.

inverted 'Y' field. As the number of linear accelerators with electron beams increased in Brazil, we created in 2014 another postal system (Fig. 2) to evaluate the main parameters of electron beams: absorbed dose at the reference depth (Z_{ref}) and absorbed dose at the range of 85% depth dose.

Our postal systems use TLD-100 powder. Our TLD laboratory follows the IAEA TLD laboratory directions and is submitted once a year to the IAEA comparison. We use two Fimel TLD readers. One technician performs all the TLD laboratory activities. Besides him, we have two physicists working in the postal radiotherapy audits. The TLD postal audit program is an important complement of the on-site audits. It is very useful for countries which have a

large number of radiotherapy machines and/or large distances to be covered with its low cost.

The analysis of the main errors and problems found in our audits, proved the necessity and importance of permanent training. Therefore, we created special courses for medical physicists, mainly e-learning courses.

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National auditing system in radiotherapy in the Czech Republic

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The National Radiation Protection Institute (NRPI) in Prague performs audits of radiotherapy units since 1996. The system of audits consists of remote and on-site audits. Since 1996, 251 radiotherapy units (889 beams) have been audited on-site and 1,912 beams through the TLD postal audit service. The system of audits in radiotherapy in the Czech Republic is described in Table 1.

For both types of audits, two national recommendations were published. The methodology, instructions, questionnaires, list of audited parameters, and report description are included.

1. On-site audits

NRPI started with basic dosimetry audits aimed at the verification of basic parameters of radiotherapy units. From the beginning, the agreement between treatment planning systems and measurements has been the point of interest. Later, more advanced audit types were developed (e.g. end-to-end audits).

1.1 Basic dosimetry audit

In the following paragraphs, audited parameters for specific treatment units are stated.

Surface and ortovoltage X ray therapy unit: absorbed dose to water at the reference point, half-value layer, radiation field (dimensions), dose rate at the depth of maximum,

absorbed dose to water under non-reference conditions, percentage depth dose.

Linear accelerator and Cobalt unit (when relevant):

absorbed dose to water under reference conditions, beam quality index, output factors, wedge factors, percentage depth dose curve, accuracy of optical distance indicator, collimator, light and radiation axes agreement, radiation and light fields agreement, isocentre stability, lasers, couch tests (vertical, longitudinal and lateral movement, horizontality), MLC transmission, dosimetric leaf gap.

Tomotherapy: couch parameters, lasers, distance between virtual and unit isocentre, percentage depth dose, output factors, MLC transmission, dose rate for static fields, absorbed dose to water, lateral and longitudinal profile, synchronous movement of couch and gantry, correct dose delivery after interrupted treatment.

Cyberknife: beam quality index, absorbed dose to water under reference conditions, output factors, percentage depth dose.

Proton therapy: absorbed dose to water (in water phantom), absorbed dose to water at different depths in anthropomorphic phantom.

HDR brachytherapy unit: air kerma strength, absorbed dose to water calculation around radioactive source, reconstruction process, source positioning in the applicators.

TABLE 1. OVERVIEW OF AUDITS IN RADIOTHERAPY IN THE CZECH REPUBLIC

| <i>Audit name</i> | On-site audit | | | Postal TLD audit |
|--------------------------------|---|---|--------------------------------------|----------------------------------|
| | On-site audit of unit | End-to-end audit of prostate radiotherapy | End-to-end audit of H&N radiotherapy | Postal TLD audit in radiotherapy |
| <i>When audit is performed</i> | After acceptance test | After acceptance test | After acceptance test | Once per 2 years – each beam |
| <i>Audited unit</i> | LA, Co, X-ray, BRT, CyberKnife, Tomotherapy, Proton unit, TPS | LA, Tomotherapy, Proton unit, TPS | LA, Tomotherapy, Proton unit, TPS | LA, Co, TPS |

LA — linear accelerator, Co — Co-60 unit, X ray— surface or ortovoltage X ray therapy unit, BRT — brachytherapy HDR unit, TP S—Treatment Planning System, R&V — Record and Verify System

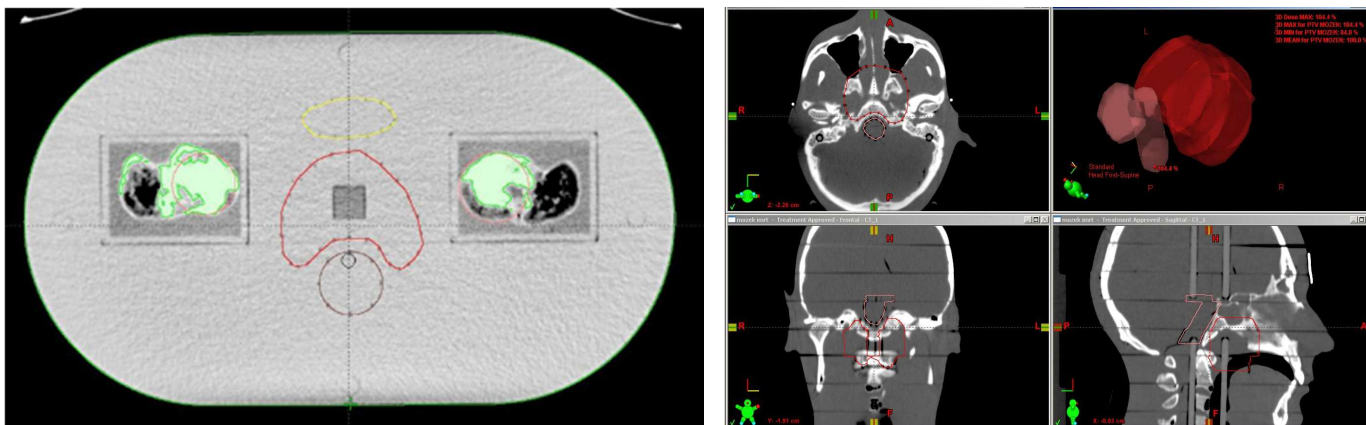


Figure 1. CT scan of pelvic phantom (left). CT scan of H&N phantom (right).

1.2 End-to-end audit

End-to-end audits are performed for prostate and H&N treatment with anthropomorphic phantoms. Physicists in the audited centre create clinically acceptable treatment plans. The dose is verified by ionisation chambers in PTV and the organ at risk. Radiochromic film (EBT3) is placed between phantom slabs to evaluate the agreement between measured and planned 2D dose planes. Except this dosimetry part of the audit, contouring, treatment planning and DVHs are evaluated.

2. TLD audits

TLD audits are carried out via postal dosimetry checks. The dosimeter used is a closed opaque cylindrical polyethylene waterproof capsule filled with lithium fluoride powder LiF:Mg,Ti (type MT-N, TLD Poland). The TLD readings are performed by means of a manual Harshaw 3500 reader. An acceptance level of $\pm 3\%$ is set for the relative deviation between the TLD measured dose and the dose stated (calculated) by the radiotherapy centre. Currently, several TLD audit methodologies are available.

2.1. Basic TLD audit

The regular basic TLD audit consists in beam calibration checks. Currently, 95% of results are within the $\pm 3\%$ limit. Higher deviations usually are connected with incorrect performance of the irradiation.

2.2. More advanced TLD audits

More advanced audits enable dose checks in more complex irradiation conditions. The particular methodologies were developed and implemented in the frame of several research projects coordinated by the IAEA; these include dose checks for various radiation fields formed by MLC and for other non-reference conditions, particularly dose measurements in special phantoms including inhomogeneities. Recently, all Czech radiotherapy centres equipped with modern linear accelerators were subjected to the TLD audit for 3D conformal radiotherapy. This included TLD measurements in a phantom with lung and bone inhomogeneities. 70% of the participants complied with the limit of $\pm 3\%$ in the first round of this audit, so there is still room for improvement of the clinical practice in the Czech Republic.

Equal-Estro experience in dosimetry audits in advanced techniques of radiotherapy – the tomotherapy example

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1. Introduction

The Equal-Estro laboratory (Equal) is accredited since 2004 for dosimetry audits of radiotherapy systems in France. To date, more than 9000 therapy beams, photons and electrons, were tested using a remote TLD method [1–3], within a

mandatory audit program of beam calibration parameters [4].

In parallel with other national and international auditing bodies [5–8], Equal has developed, and made available for more than 10 years, novel methodologies designed to conduct dosimetry audits of advanced radiotherapy

techniques and treatment machines. These include audits of IMRT, VMAT, Tomotherapy and CyberKnife systems.

2. Materials and methods

2.1. Equal-Estro dosimetry audit

All audit services provided by Equal are based on remote procedures, using TLDs or TLDs and films. The TLDs are used for point-dose measurements, whereas films are employed for 2D dose distribution measurements.

For advanced techniques in radiotherapy, Equal provides end-to-end dosimetric tests by the means of phantom irradiation. The audited centre receives the phantom together with planning CT images as well as the corresponding conversion curve. The planning for the irradiation of the phantom has to be prepared by the audited centre as per the protocols applied in the centre. The only constraint imposed by Equal is the maximum prescription dose which must be no higher than 8 Gy.

2D film images are compared to TPS plans, taking into account the acceptability criteria as follows:

- Dose deviation should be less than 10% for at least 90% of the film area;
- Gamma-test passing rate, at 5%/3 mm and 5% dose threshold, should be higher than 90%.

TLDs are used for the beam output tests, to be irradiated separately from the phantom, in the reference conditions. The acceptability criteria for TLD measurements correspond to the maximum acceptable dose deviation of 5%.

2.2. Dosimetry systems

The TLDs provided by Equal are powder-type dosimeters using TLD-700® lithium fluoride (LiF) encapsulated in polyethylene tubes. The active volume of these dosimeters is 20 mm in length and 3 mm in diameter. The reading is performed with an automated PCL-3 reader from Fimel (France).

For the film measurements Gafchromic™ EBT3 (Ashland Specialty Ingredients, Bridgewater, NJ, USA) films are used. The readout of films is performed using a commercial flatbed scanner Epson® Expression® 10000XL. Film images are compared to TPS plans using a commercial IMRT QA software, OmniPro I'mRT (IBA Dosimetry).

2.3. The phantom

For the dosimetry audits of Tomotherapy systems a water equivalent geometric phantom is used (Fig. 1). It is based on a commercial homogeneous phantom to which inhomogeneities were added in terms of lung equivalent inserts as well as bone equivalent inserts. The phantom allows the positioning of films in the axial, coronal or sagittal orientation with dimensions of up to 16 cm x 16 cm.

The phantom charged with three films is sent to the audited centre in a shipment case.

3. Test Results

In this paper we are presenting the results of Tomotherapy systems end-to-end audits in France during the past five years, from 2014 to the end of 2018. Overall, 43 tests were performed in this period, with some of the treatment units being audited more than once.

3.1. Reference beam output tests/ TLDs

The reference beam output tests, using TLD measurements (Fig. 2), show the results in the acceptable range for all tested units. Moreover, for almost 90% of the tested units the measured dose deviation is within 1%. Only one unit showed the deviation in the range of 3 to 5%.

3.2. Dose distribution measurements / films

Relative to the first acceptability criteria for films, the measurements showed the acceptable results for all tests. For the second criteria, related to the gamma test, the results were similar with the exception of one test for which the gamma passing rate was lower than the limit of 90% (Fig. 3). Nevertheless, for more than 70% of tested units the passing rate for gamma tests is higher than 95%.

4. Conclusion

Over the last 5 years, from 2014 to 2018, the results of the reference beam output measurements with TLDs performed by the Equal-Estro laboratory on Tomotherapy systems in France are highly satisfying, as no deviation over the 5% limit was found.

At the same time, the film tests show the acceptable results for over 98% of cases. Starting with 2019 a new test is proposed with more restrictive acceptability criteria for films.

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A dosimetry audit for radiotherapy departments in Germany

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Why do we need it? — The German requirements



The correct application and traceability of radiotherapy dose measurements in Germany traditionally rely on calibrations of Co-60 (and orthovoltage qualities if necessary) and use of a national code of practice (DIN 6800-2).

With the advent of the European Medical Device Directive and its transposition into German law, the necessity for surveillance of the clinical dosimeters as medical products was recognized. Accordingly, these instruments were included in the German Medical Product User Directive [1] stipulating a control of all dosimetry equipment clinically used every two years.



Fig. 1. TLD discs and the irradiation holder.

How is this done? — An elaborate TLD-procedure

The committee responsible for this part of the MPBetrV agreed on a 3% intervention limit for the dose measurement using high energy beams in the clinic. This requires a 1% uncertainty of the comparison measurement resulting in the need for a 0.3% repeatability towards the National Laboratory, Physikalisch Technische Bundesanstalt. To achieve this very high measurement accuracy, a special TLD holder and the relevant procedure were developed with the help of Dr. Feist, Munich.

High expectations — Start in 2001

It took nearly two years to develop, commission and validate the new TLD laboratory at PTW. Luckily the customer response was slow too, at the beginning allowing the lab to grow in the meantime. Among the first customers was one

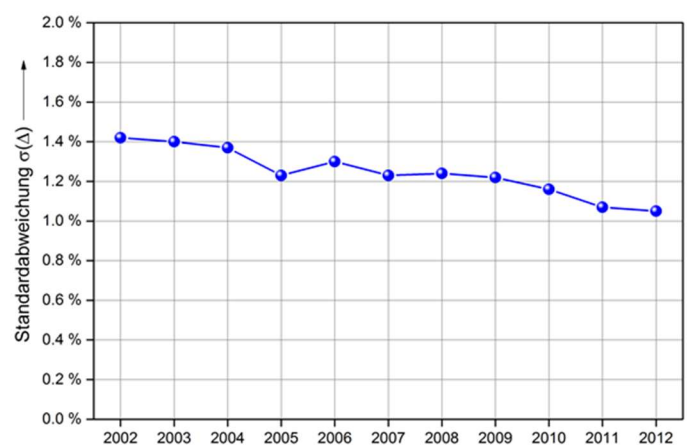


Fig. 2. Trend of the standard deviation of positive audit results [2].

who believed so strongly in the audit and in their dosimetry practices that they complained about a deviation of just 1%. Evaluation of their measurements showed that this was justified. The department was using a new draft version of DIN 6800-2 while the lab was using the still valid “old” version. Most of the small deviations then could be traced to that difference.

Photon catastrophe — How to achieve strange results

With the years audits became routine and that presented with some dangers. One perfect example of this was a set of results which were excellent for electrons and completely dissatisfactory for photons. The reason was quickly identified: A physicist had done the difficult electron measurements himself and had left the less complicated photon component to an assistant who had not understood the actual task.

Bettering the world — Visible improvements

Nevertheless, single events like this could not spoil the whole picture for audits. With the procedure becoming established in clinical practice and increasing experience from lessons learned being applied, the number of failed results was falling constantly. The audits also proved to be a motivation for more regular recalibrations of equipment. As a result, not only the number of failures but also the accuracy of positive results improved consistently. An investigation by PTB resulted in a presentation during the 2013 German Medical Physics Convention by Dr. Kapsch where among others the graph given in Fig. 2 was shown.

The present — Who, where and how

In today’s PTW TLD lab three experienced technicians operate three venerable FIMEL PCL3 readers. The Harshaw TLD100 chips are then annealed using original PTW ovens. Normally the chips are irradiated in small calibration water phantoms (which are also shipped to the customer upon request); adaptors for other water phantoms are available.



Fig. 3. View of the PTW TLD laboratory.

The lab typically serves about 120 German customers every year. Given that each radiotherapy department has to check the lowest and the highest photon and electron energies used and some also check the intermediates, this results in a yearly workload of over 500 beams.

Recently also some international customers have used the service; this has shown that the TLD evaluation procedure even accommodates the consequences of air transport and longer reading delays.

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Dosimetry audits in radiotherapy in Greece: 15 years of experience and contribution to safety

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Since 2001, the Greek Atomic Energy Commission (EEAE) provides dosimetry audits (DA) [1] in MV photon and electron beams and in brachytherapy in all 32 radiotherapy

(RT) centers across the country, operating 47 Linacs, 2 SRS/SRT systems, 2 Co-60 units and 9 HDR Ir-192 brachytherapy systems. It is estimated that 70 working hours



Fig. 1. The phantoms used in DAs: Water, polystyrene (cube and oblique options), CIRS head and neck phantom and RTSafe pseudo-patient head phantom

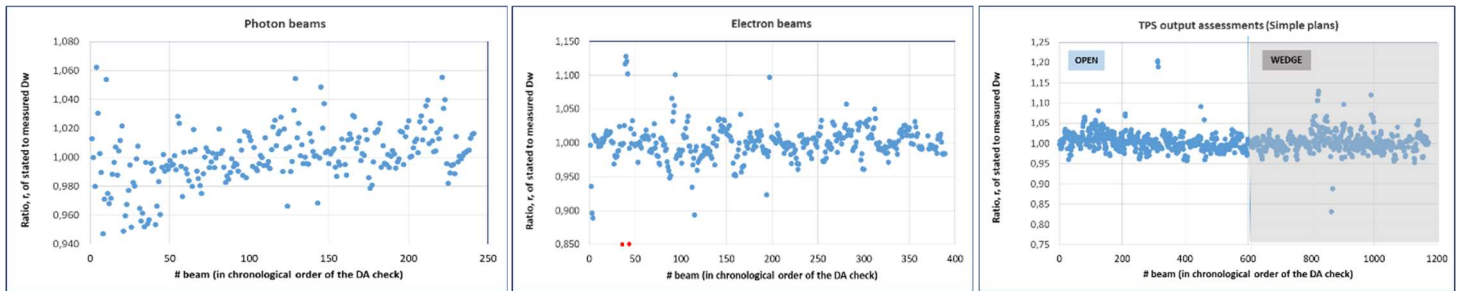


Fig. 2. The ratios, r , of the stated to measured D_w : reference dosimetry of 241 photon and 382 electron beams and TPS evaluation with dosimetry under non-reference conditions (790 open & 344 wedged photon beams). The tolerance levels are $\pm 3\%$ and the acceptance limits $\pm 5\%$. The expanded uncertainty is approx. 3% ($k=2$).

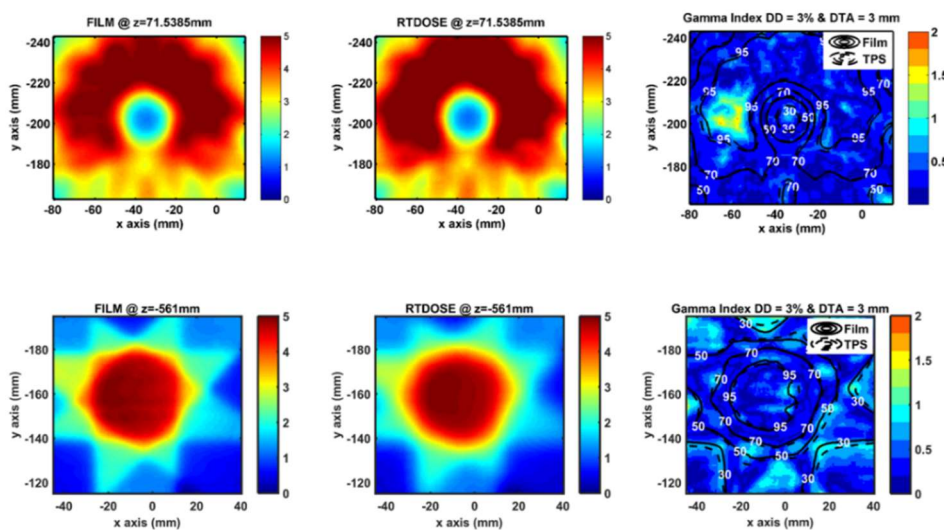


Fig. 3. DAs using 2-D film dosimetry. Typical VMAT with a C-shaped PTV (upper) and a 3D-CRT with a spherical shaped PTV treatment plans (lower). Left images: film dose distributions measured by EAE with the CIRS phantom. Middle images: dose distributions from the TPS of the RT center. Right images: Gamma index maps (3%/3mm) with selected measured (solid lines) and calculated (dashed lines) percentage isodose lines superimposed on the colormap.

are needed for a complete DA procedure; 10 to 15 hours are spent for each on-site visit. The EAE cooperates closely with the EAE's secondary standard Ionizing Radiation Calibration Laboratory (IRCL/EAE-EIM).

Every 5 years the EAE conducts a round of dosimetry audits during which all RT centers are audited. Within the same DA round, a RT center may be audited several times. The participation of the RT centers in the dosimetry audit is mandatory, as part of the authorization process. However, often, RT centers request voluntarily to go through the audits

for the verification and inter-comparison of their dosimetry and RT procedures applied.

The audit levels [2] applied in sequence are: mechanical and functional tests of the RT systems, dosimetry under reference and non-reference conditions (level 1 & 2), treatment planning system (TPS) output verification through dose measurements (level 3) and end-to-end tests (level 3 and 4) for the assessment of the TPS dose calculations in conventional and advanced radiotherapy techniques with 1-D dosimetry (ionization chambers), 2-D (film dosimetry) and 3-D procedures (gel dosimetry). Analytical estimation

of uncertainties has been performed and tolerance levels and limits have been determined, accordingly. Appropriate dosimetry equipment and water, plastic and anthropomorphic phantoms are used (Fig. 1).

DAs demonstrated that the accuracy of the dosimetry under reference and non-reference conditions for photons and electron beams improved over the years. Moreover, the end-to-end dosimetry tests and the results for IMRT, VMAT and SRS gave acceptable results in most cases

Several factors that may influence the patient's treatment accuracy have been identified through DAs, which present a decreasing incidence over the years. Inadequate practices or misuses were reported and discussed with the RT staff on site. Indicatively, issues regarding the beam output check, dosimeter calibration, inconsistencies in relative dosimetry (e.g. PDD, R50) and dosimetry protocol application, lack of equipment (barometer), errors and bugs in home-made dosimetry algorithms, personal resources, operational procedures, etc. occurred.

The contribution of EEAE DAs to the improvement of dosimetry practices is evident and some of the main achievements are the identification of discrepancies in dosimetry that the radiotherapy staff were unaware of; the

enhancement of the radiotherapy staff's confidence in patient dosimetry, the harmonization of dosimetry procedures countrywide by implementing a common dosimetry protocol [3], verification of the geometric and

dosimetric accuracy of the whole radiotherapy chain (end-to-end) and the dissemination of knowledge, expertise and experience between the EEAE and the radiotherapy staff. DAs in RT are supported and performed on a regular basis, in order to keep pace with new technologies.

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Postal dose audit in Japan: ten years' experience

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The organization, staffing and resources for the audit network

In Japan, the service of postal dose audits for radiation therapy units have been performed since 2007. The technological aspects of the audit were developed by the National Institute of Radiological Sciences (NIRS) and the actual audit to radiotherapy hospitals has been operated by the Association for Nuclear Technology in Medicine (ANTM). Being an SSDL, in collaboration with NIRS, ANTM also has operated the calibration services for ionization chambers. Six technical staffs of ANTM are engaged in the routine audit work and SSDL calibration tasks. Audits are financed by fees paid by participating hospitals. In Japan, the external dosimetry audit has not been mandatory for radiotherapy hospitals. In 2018, the audit became mandatory for designated cancer hospitals. We recommend participation in the audit every three years.

The tools used in the audit

The radiophotoluminescent glass dosimeter (RPLD) was used in the audit [1]. The RPLD system, the Dose Ace (ASAHI GLASS CO.), is commercially available in Japan.

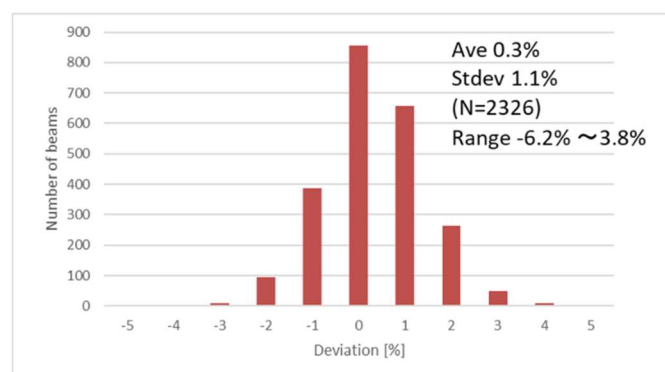


Fig. 1. Deviation of the results of the postal dose audits of radiotherapy hospitals for the delivery of absorbed dose to water under reference condition during 2007-2017.



Fig. 2. The members of NIRS/ANTM audit group.

RPLD characteristics such as repeatable readout and the negligible fading effect are suitable for the postal dose audit. RPLDs and a water equivalent solid phantom (Tough Water Phantom, KYOTO KAGAKU CO.) were sent to radiotherapy hospitals, where the RPLDs were irradiated with high energy X ray beams. Irradiated RPLDs were then sent back to NIRS/ANTM for evaluation. The audit began with the reference conditions (10 cm x 10 cm field, 10 cm depth) and expanded its application to beams of different field sizes (from 5 cm x 5 cm to 25 cm x 25 cm) and wedged beams (15°, 30°, -45°, -60°) in 2010 [2]. In 2016, audits were made available for flattening filter free (FFF) beams from modern accelerators, Tomotherapy, and Cyberknife beams. The tolerance level was set to $\pm 5\%$ considering the uncertainty of $\pm 1.1\%$ (1 SD) for the reference conditions. The uncertainty is greater for non-reference conditions with the maximum value of 1.8%, for FFF beams.

The SSDL-ININ Mexico dosimetry audit network experiences

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Introduction

In the Mexican Republic there are currently around 125 radiotherapy centers that provide treatments with external photon beams and brachytherapy.

With the purpose of contributing to the quality of the physical dosimetry for these treatments, the SSDL-ININ organizes postal audit programs through three main activities:

1) In the case of external radiation beams, annually, about 10% of radiotherapy centers are selected to participate in the IAEA's and the ININ's postal audit programs, in terms of absorbed dose to water D_w , [1, 2],

The audit results

By the end of the Oct. 2017, 2326 beams were checked in the reference conditions. Including non-reference conditions, 4579 beams from 470 hospitals were checked.

The distribution of the audit results for the reference conditions is shown in Figure 1. The results correspond to the percentage ratios of the NIRS RPLD evaluated dose to that stated by the user, D_{RPLD}/D_{stat} .

The mean percentage ratio was 0.3%, and the standard deviation was 1.1%. Regarding the spread of the audit results, 99.9% beam checks were within the tolerance level of 5%. However, 5 results exceeded the tolerance level of 5%. In most cases, there were mistakes in the data sheets provided by the participants that were clarified through the follow-up. This activity has certainly improved the quality of radiation therapy in Japan. More efforts are underway, such as an application of the audit system to electron beams and intensity modulated radiation therapy.

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2) Pilot program of D_w postal audit for brachytherapy in low and high dose rate, to the energy of ^{137}Cs and ^{192}Ir , respectively, [3, 4]

3) Postal audit program for verification of SBRT and IMRT treatments, [5, 6].

The SSDL-ININ is a part of the IAEA/WHO network of secondary standards laboratories since the 1970s, and continually it has participated in the coordination of the IAEA's dosimetry audits in Mexico. In 2006, the SSDL-ININ developed the infrastructure for the implementation of a D_w pilot postal audit program parallel to that offered by the IAEA.

TABLE 1. RESULTS OF THE SSDL-ININ ACTIVITIES FOR THE DOSIMETRY AUDIT PROGRAMME.

| Year | External beams | | | Fails | % Fails | Hospitals | Remarks |
|--------------|----------------|------------|------------|-----------|------------|------------|-----------|
| | Co 60 | Linacs | Total | | | | |
| 2009 | 11 | 7 | 18 | 4 | 22% | 13 | IAEA/ININ |
| 2010 | 2 | 6 | 8 | 0 | 0% | 8 | IAEA/ININ |
| 2011 | 1 | 9 | 10 | 1 | 10% | 8 | IAEA/ININ |
| 2012 | 6 | 0 | 22 | 2 | 9% | 13 | IAEA/ININ |
| | 2 | 9 | 11 | 4 | 36% | 4 | ININ |
| 2013 | | 14 | 14 | 2 | 14% | 6 | IAEA/ININ |
| | 37 | 0 | 37 | 4 | 11% | 37 | ININ |
| 2014 | 5 | 16 | 21 | 1 | 5% | 15 | IAEA/ININ |
| 2015 | 2 | 24 | 27 | 4 | 15% | 13 | IAEA/ININ |
| 2016 | 7 | 25 | 32 | 2 | 6% | 18 | IAEA/ININ |
| 2017 | 2 | 21 | 22 | 2 | 9% | 11 | IAEA/ININ |
| 2018 | 2 | 17 | 19 | 0 | 0% | 11 | IAEA/ININ |
| Total | 77 | 148 | 241 | 26 | 11% | 157 | |

The staff of the SSDL-ININ pilot program comprises of two dosimetrists and one technician.

For dosimetry audits the SSDL-ININ uses TLD powder with Harshaw 3500 TLD reader. For brachytherapy audits it uses a specially designed acrylic phantom. The details are given in references [1-5].

Current and past activities

Table 1 summarizes the external beams D_w postal audit results from 2009–2018.

The principal causes of deviations from the D_w reference dose are, [2]:

- Misperception in the calibration setup: the source axis distance (SAD) setup is confused with the source skin distance (SSD) setup;
- Misunderstanding of the reference dose clinical D_w at d_{max} , with the D_w at the calibration reference point: $d_{ref}=10$ or 5 cm;
- Calculation of the D_w with the TPS without manual verification of D_w value;
- Operation of the electrometer in the dose mode, without the verification of the electrical quantities, calibration and correction factors;
- Rounding errors of the measurements and/or calculations;
- Lack of traceability in atmospheric pressure measurements.

Acknowledgments

We would hereby like to acknowledge the IAEA staff of the Dosimetry Laboratory for the support given to us over the years, and to the Mexican medical physicists that daily contribute to the safety and health of the patients.

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Dosimetry audits in radiotherapy by the SSDL in Poland

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The Polish Secondary Standard Dosimetry Laboratory of the Oncology Centre in Warsaw was created in 1966. It is a continuation of the Physics Laboratory founded in 1934 based on the plans of Maria Skłodowska-Curie, founder of the Radium Institute opened in Warsaw in 1932. Since its inception, the Physics Laboratory was devoted to developing methods of measurement of radiation delivered to patients being treated in the home institute, as well as for the control of radiation delivery in other hospitals. This task was performed by the X ray and Radioactive Substances Calibration Laboratory opened at the Physics Department in 1937 following governmental regulation. World War II put an end to this activity, which was re-established in 1951, when the Central Laboratory of Radiological Measurement was created. In 1966, the laboratory was upgraded and given the status of a Secondary Standard Dosimetry Laboratory, approved by the Polish Primary Standard Dosimetry Laboratory. Since 1988, the laboratory in Warsaw is a member of the IAEA/WHO Network of SSDLs and provides calibration of therapy level dosimeters with cylindrical or plane-parallel ionization chambers in a Co-60 beam, and with well chambers using an Ir-192 source.

Since 2014, the SSDL in Warsaw is an accredited calibration laboratory according to the ISO/IEC 17025 standard (Figure 1) and is annually audited by the Polish Centre for Accreditation – a member of the International Laboratory Accreditation Cooperation (ILAC) association.



Fig. 1. Accreditation symbols of the Polish SSDL from the Polish Centre for Accreditation for the calibration of dosimeters (left) and the postal TLD dosimetry audits (right).

In Poland, there are currently 38 radiotherapy centres equipped with 149 accelerators (Figure 2).

Since 1991, the SSDL carries out TLD postal dosimetry audits in all Polish radiotherapy centres. The audits are performed on a yearly basis. Initially, the audits were carried out in reference conditions only, but since 2004, they were carried out mostly in non-reference conditions. In recent years the results of the audit were within $\pm 3,5\%$ even in non-reference conditions.

Over the last seven years, several dosimetry audit methods, including the “end-to-end” type, were introduced and tested by the SSDL in Warsaw, for quality evaluation of the 3D conformal radiotherapy (3DCRT) and intensity modulated radiation therapy (IMRT) technique performance in Polish oncology centres. Currently, the methods of auditing new and complex techniques are introduced and tested in collaboration with the IAEA.

Quality evaluation of the 3DCRT was performed in 8 centres [1]. An audit of small field output factor calculations in radiotherapy was performed in 32 Polish radiotherapy centres [2]. An end-to-end audit of IMRT dose delivery was performed in 12 Polish radiotherapy centres. Based on the results of the audits, some participants performed new measurements and changed the beam modelling in their TPSs or replaced the obsolete calculation algorithms with advanced ones. In another institution, following the audit

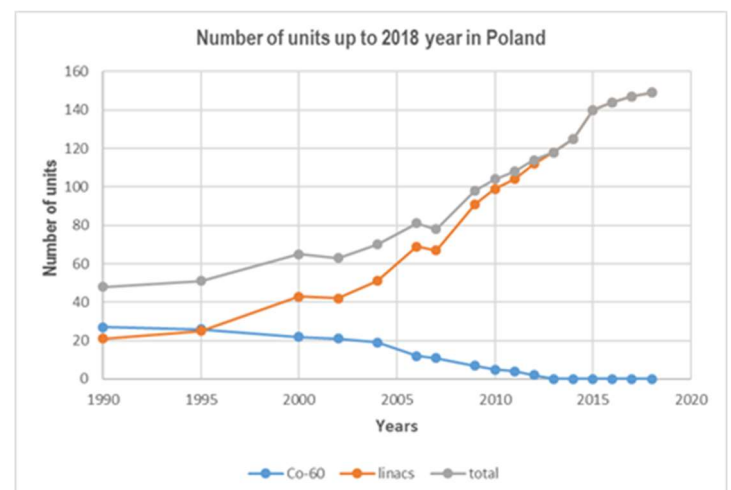


Fig.2. Number of radiotherapy units in Poland.

results, the alternative beam models were created for the same beam, which then were optimized and tested.

The participants are satisfied with participation in the audits, because it provides the opportunity to ensure or to improve the quality of the radiotherapy carried out in their institutions.

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The Dutch dosimetry audit network

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Introduction

Dosimetry audits in the Belgium-Dutch region have been developed by the Nederlandse Commissie voor Stralingsdosimetrie (NCS) <https://radiationdosimetry.org>. The NCS is a non-profit organization with the aim of promoting the appropriate use of dosimetry of ionizing radiation both for scientific research and for practical applications. Hence, the reports are freely available on-line, sometimes complemented by publications in peer reviewed journals. The foundation is supported by member societies. Each society has a delegate represented in the NCS board, consisting of 11 members. The Dutch Metrology Institute, VSL, is closely connected to the NCS by providing the secretary board member.

Dosimetry Audits in Belgium and The Netherlands

In the Belgium-Dutch region there is history of self-organized (inter-institute) dosimetry audits [1, 2]. However, in the last 10 years, several NCS activities on dosimetry audits took place, resulting in NCS reports 23, 28 and 29 [3-5]. These projects were carried out by Medical Physicists and Medical Physics Engineers, in cooperation with VSL. The on-site dosimetry audits for MV photon and MeV electron beams were published in NCS reports 23 and 29. Results from the electron audit and the IMRT-VMAT audit were additionally published in phiRO [6, 7]. Currently, the photon and electron audits are provided as fully accredited services by VSL according to ISO 17043 for proficiency tests (PTs) and ISO 17025 for calibration labs. NCS report 28 is currently developed into new a VSL PT service. Despite that both Dutch and Belgian societies are members of the NCS, the majority of the NCS audits took place only

in Dutch institutes. In Belgium, dosimetry audits are arranged by the BeldArt under the auspices of the Federal Agency for Nuclear Control and the Belgian College of Radiation Oncology.

The NCS' experience with organizing dosimetry audits is that it is a time-consuming and labour-intensive task. It takes considerable effort and (free) time from the subcommittee members. Besides, it is a cumbersome task to select, summarize and report the relevant results. Since all audits were performed on-site, where the audit team visited the institutes, usually the institutes were grouped into smaller regions to minimize travel and time required. The photon audit was performed at 26 Belgian and Dutch institutes [3]. It showed excellent agreement with an average deviation of -0.3% and the maximum deviation of -1.4%. This was in all cases within the relative expanded uncertainty of 1.6% ($k =$



Fig. 1: Preparations for measurements during the MeV electron audit, NCS-29.

2). Moreover, the visiting nature proved worthwhile due to stimulating and enthusiastic discussions between participants and the audit team. Everyone appreciated the contact and learned from the experience, irrespective of the actual audit results.

The goal of the MeV electron audit was to quickly and effectively implement an audit within a limited number of radiotherapy institutes. This resulted in a PT-on-demand service currently provided by VSL [5, 6].

The IMRT-VMAT audit was unique in the sense that a limited set of realistic treatment plans were distributed among the institutes [4, 7]. These plans were imported in the institute's treatment planning system, delivered at the linac and assessed using local QA procedures. In fact, the comparison between the audit and the institute provided insight in both forms of QA. The most important insight was that all institutes optimised their treatment planning system (e.g. description of leaves) and procedure (allowed class solutions) to the deviations found with their phantoms, as was to be expected. The effect is that there is an interconnectedness between QA devices and the treatment planning system. Using externally devised realistic treatment plans circumvents this to some extent.

Continuity

The upside from a volunteer-based audit is the low costs and the possibility to make it exciting, however, the disadvantage is, that it is rather elaborate and complex. In addition, the way these NCS audits are organised ensures in general a 100% participation within a rather short time span (months), making it possible to make a regional comparison. The downside is the lack of continuity and the possibly long duration of the whole procedure to compose a subcommittee, perform the audit visits and finalize the

report. Therefore, it was found convenient that more continuous alternatives are being developed by VSL.

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Radiotherapy dosimetry audit network in the United Kingdom

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Dosimetry audits have developed steadily over the past 30 years in the United Kingdom (UK). The national groups supporting audits include the UK Interdepartmental Dosimetry Audit Network which was formally established in 1993, the National Physical Laboratory (NPL) which was established in 1995 and the UK Radiotherapy Clinical Trials Quality Assurance (RTTQA) which has been active since 2000.

Institute of Physics and Engineering in Medicine



In the UK, the first comprehensive national photon dosimetry inter-comparison was carried out in the late 1980s and laid the foundation for the development of a national dosimetry audit network, which began to

evolve in the early 1990s. The UK Interdepartmental Dosimetry Audit Network grew from this and currently consists of 9 cooperative regional groups co-ordinated by the Institute of Physics and Engineering in Medicine (IPEM). Each group consists of typically 6-8 centres and each centre will both host and receive a dosimetry audit visit in a round robin style organisation. A key strength of the interdepartmental audit system is that every NHS department in the country is involved, thereby providing an opportunity for peer comparison.

National Physical Laboratory



In 1995 the National Physical Laboratory (NPL) began reference audits within the UK at the invitation of IPEM, initially to link

the regional audit network groups. Within this network, the basic audit methodology and phantom design followed that of the national intercomparisons. As the National Physical Laboratory is the UK's primary standards laboratory, the Radiation Dosimetry Group is responsible for maintaining the primary standards for external beam radiotherapy. All UK NHS external beam radiotherapy treatment doses are traceable to the primary standards via NPL's dosimetry calibration services. Whilst maintaining audits of reference dose, NPL has broadened its involvement in dosimetry audits to cover clinical dose delivery of typical treatment modalities, via the use of its alanine measurement system.

National Radiotherapy Clinical Trials Quality Assurance Group



The UK Radiotherapy Clinical Trials: Quality Assurance Group has also evolved, beginning around

2000 and supporting quality assurance (QA) for specific 3DCRT and later IMRT clinical trials. This activity gave rise to the National Radiotherapy Clinical Trials Quality Assurance Group, known as RTTQA, in 2003. Audits for clinical trials have created a strong basis for verification of existing and new techniques in radiotherapy in the UK. The majority of centres now participate in multiple trials and hence have access to a high level of regular audits through the QA processes of these trials.

National audit programmes

The original UK dosimetry intercomparison involved participation of the then 64 UK radiotherapy centres. The audit network progressed from the early 90s with each regional group carrying out its own audits, to suit the local resources and requirements, linked by the NPL inter-group audits and liaising through the national (IPEM) steering group. The first nationally coordinated audit within the current structure of the IPEM interdepartmental audit groups was an MV photon audit in 2008.

In the past 10 years there have been several national UK audits which have helped to support the implementation of, and set the standards for, advanced techniques. These have included a national IMRT audit, a rotational IMRT (VMAT and Tomotherapy) audit. National dosimetry audits for SRS (stereotactic radiosurgery), brachytherapy and Stereotactic Ablative Body Radiotherapy (SABR) in the lung and in the spine have also been completed. Other novel techniques which have been recently audited include intraoperative radiotherapy, using compact mobile kilovoltage X ray sources for the treatment of breast and other cancers.

Modern radiotherapy is complex to plan and deliver accurately and departments need to demonstrate that the risk to patient safety is managed. New treatment techniques are typically developed and first implemented in a few centres, often as the prelude to, or as part of, a clinical trial. A collaborative approach to audits across NPL and RTTQA has supported centre accreditation for inclusion in clinical trials. Audits may begin as specific clinical trial audits but subsequently develop into more routine approaches.

Conclusion

Overall, the track record of the UK audits has demonstrated confidence in dosimetry for clinical practice and for trials, and continues to do so. The audit system is one strand in a regulated dosimetry infrastructure in the UK, providing a system of dosimetry with high consistency which consists of: the national dosimetry standards (NPL); the UK dosimetry codes of practice, specifying defined transfer instrumentation and procedures (with one specific recommended secondary standard chamber and consistently specified and used tertiary dosimeters); the national quality assurance recommendations (IPEM); and the national audit network (NPL, IPEM and RTTQA).

The IAEA methodologies for 'end-to-end' on-site audits

J. Izewska

International Atomic Energy Agency

The IAEA 'end-to-end' audit methodology was first developed for 3 D conformal radiotherapy (CRT) in 2008 [1]. It reviewed the dosimetry, treatment planning and radiotherapy delivery processes using the 'end-to-end' approach, i.e. following the pathway similar to that of the patient, through imaging, treatment planning and dose delivery. The 3 D CRT audit was implemented at national levels with the IAEA assistance. The IAEA provided an anthropomorphic thorax phantom (manufactured by CIRS) and expert assistance to help launching the audit activities at the national levels. National counterparts conducted the audits at local radiotherapy centres through on-site visits. Doses calculated by treatment planning systems (TPS) were compared with ion chamber measurements performed in the CIRS thorax phantom for eight test cases. The agreement criteria were defined for each measurement point to assist assessing the performance of TPSs. The audit has been carried out in eight countries in Europe: Estonia, Hungary, Latvia, Lithuania, Serbia, Slovakia, Poland and Portugal [2]. Sixty radiotherapy centres participated. In total, about 200 data sets (combination of TPS algorithm and high energy photon beam quality) have been collected and reviewed. Discrepancies requiring follow-up occurred in about 10% of datasets. In addition, suboptimal beam modelling in TPSs was found in several centres. Overall, the TPS end-to-end audits for 3 D CRT have contributed to better understanding of the performance of TPSs and helped to improve radiotherapy physics practices related to imaging, dosimetry and treatment planning.

Similarly, to the 3 D CRT end-to-end audits, new audit procedures were developed by the IAEA in a series of consultants' meetings for end-to-end auditing of intensity modulated radiotherapy (IMRT) and volumetric arc therapy (VMAT) using on-site visits. The objective was to review medical physics aspects of the overall clinical IMRT

performance and to provide feedback to the participating radiotherapy centres regarding the quality of a typical clinical head and neck IMRT/VMAT treatment to ensure the optimal and safe usage of these techniques. The methodology simulated the important parts of the external beam IMRT/VMAT radiotherapy workflow from patient data acquisition to treatment planning and dose delivery. To be close to a realistic patient procedure, this audit uses an anthropomorphic phantom "Shoulders, Head and Neck, End-to-end" (SHANE, developed by CIRS). The audit package includes the instructions and data reporting forms, a SHANE phantom and a set of contours representing the target volumes and organs at risk [3]. The contours are electronically imported and superimposed on the CT scans of the phantom. Dose prescriptions and normal tissue constraints are provided for the preparation of treatment plan by the audited centre. The treatment plan is transferred to the linac at the centre and the dose is delivered to the phantom. Ionization chamber is used to verify the doses at specific points in the phantom. Radiochromic film is used to obtain 2 D dose distributions. Comparisons are made between the TPS calculated and the measured doses.

Pilot testing with six participants was conducted in the period from 2015 to 2017. Additional testing of the treatment planning constraints was performed in 2017 with 12 institutions participating [4]. The results of the multicentre pilot study showed that the IMRT audit methodology is feasible and the audits can be implemented at national levels similarly to the 3 D CRT end-to-end audits.

The IAEA supports the national implementation of the IMRT/VMAT audit by providing a SHANE phantom and the auditing methodology. The national auditing organizations conduct the audit at local radiotherapy centres. The dosimetry phantom is circulated among the countries participating in this project. After the completion of the audit

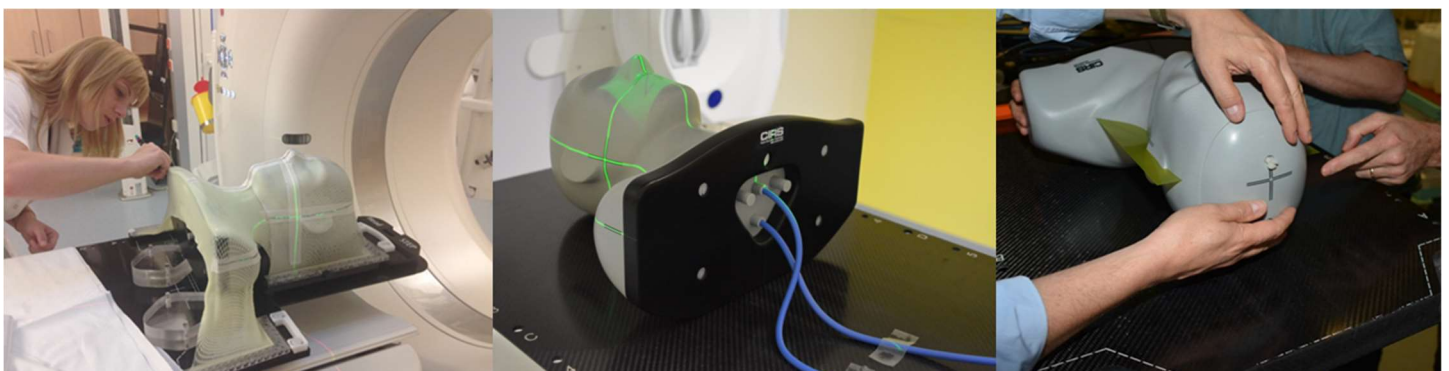


Fig. 1. Measurements using the SHANE phantom.

in one country, the phantom is transferred to the next country. To-date IMRT/VMAT end-to-end audits have been conducted in Hungary, Lithuania, Portugal and Serbia. One example of the national implementation of the end-to-end audits using the IAEA methodology is provided by Portugal in this issue [5].

The methodologies for both 3 D CRT and IMRT/VMAT audits are available on the IAEA DAN database website [6].

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The IAEA on-site IMRT/VMAT end-to-end audit: first results

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The IAEA has developed, tested and started international implementation of the audit methodology for intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) treatments of head and neck tumor site [1]. It utilizes commercially available “Shoulders, Head and Neck, End-to-end” phantom (SHANE, CIRS Inc.) and applies a two-phase approach with a part of the audit done remotely before the on-site visit takes place.

The remote pre-visit phase includes the verification of small field output factors and profiles calculations by the treatment planning system (TPS), validation of the multileaf collimator (MLC) modelling in TPS, as well as testing the capability of the audited institution to create a clinically acceptable treatment plan for the computed tomography (CT) images, contours and constraints provided. Most of these tests were earlier developed through the IAEA-organized coordinated research projects (CRPs) as separate

audit steps and thus have well-defined methodologies and tolerance levels [2, 3].

The on-site phase starts with SHANE CT scanning, which serves two purposes: acquiring imaging data for treatment planning as well as checking geometrical properties of the CT scanner and CT numbers to relative electron density (CT-to-RED) conversion. The subsequent image registration, treatment planning, patient-specific quality assurance (QA) procedures and irradiation are done the way if SHANE were a real patient. Finally, ion chamber (IC) and film measurement results are compared to the TPS calculations giving the ultimate answer regarding the overall dosimetric accuracy of the clinical IMRT/VMAT implementation.

Overall, the methodology was found to be providing a comprehensive review of physics aspects of the whole IMRT/VMAT process in a standardized and time-efficient manner thanks to its separation into two phases. Tolerance

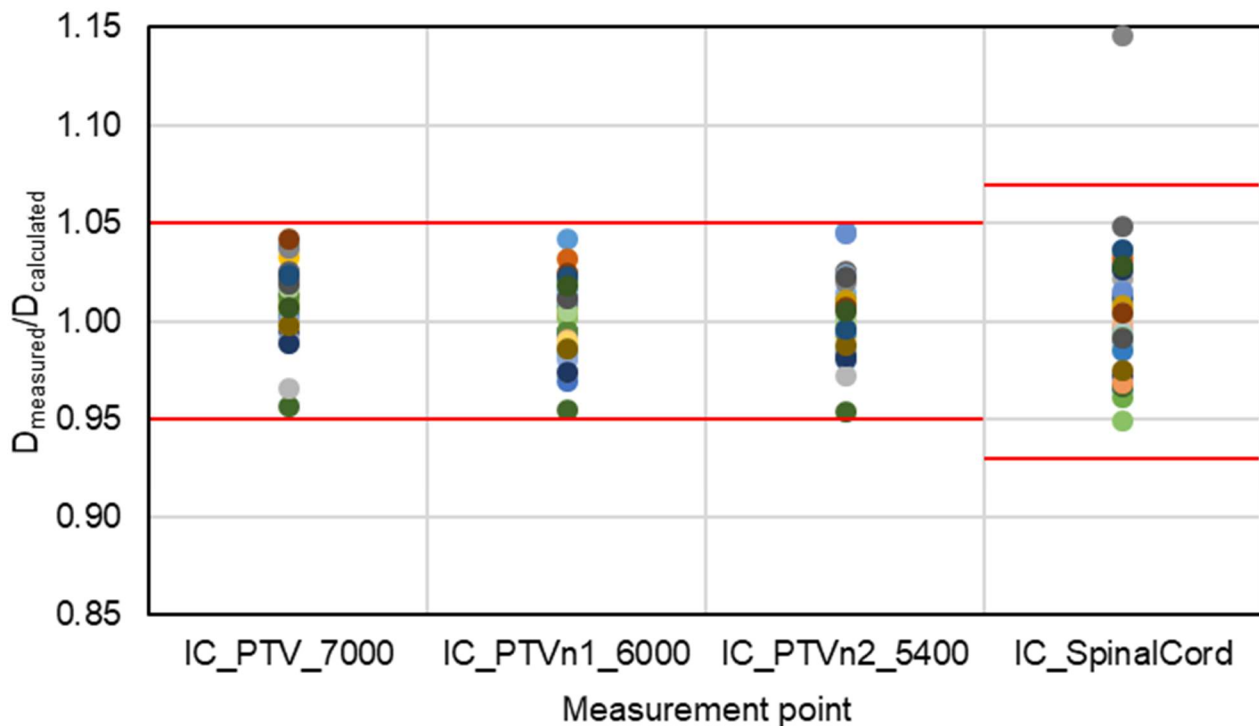


Fig.1. Ion chamber measurement results in 35 European RT centres.

limits established for every activity were found feasible, including those for IC and film measurement results in comparison with TPS calculations (5%/7% for IC measurement points in PTVs/OAR and 90% points passing global gamma criteria of 3%/3 mm with 20% dose threshold).

The audit was successfully implemented at the national level in Hungary, Lithuania, Portugal and Serbia with 35 institutions participating. Another 16 countries are planning to organize nation-wide audits in 2019-2021 with the support of the IAEA.

Current findings of the international audit implementation include:

- very good results of IC and film measurements within established tolerances (Fig.1, 34/35 institutions passed it from the first attempt);
- suboptimal CT-to-RED curves exceeding tolerance limits particularly for points of higher density such as cortical bone and trabecular bone (32/35 cases at least one point out of tolerance);
- suboptimal small field output modelling (13/35 cases at least one point out of tolerance);
- questionable small field profile modelling with rather high spread of penumbra sizes even among the same linacs and TPSs.

Final results of the wide international implementation of the audit will provide more data to analyze. It is expected that the current tolerance levels for both IC and film measurements may be reviewed and possibly narrowed. Additionally, analysis of treatment plans generated by participants against different complexity metrics may show some correlations with measurement results. It has already been proved that the audit methodology can be successfully applied within QUATRO missions [4] to advanced RT institutions thus giving additional angle on their clinical practices.

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Dosimetry audits – the Portuguese experience

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Portugal has an estimated population of 10.3 million inhabitants, including the mainland, in the Iberian Peninsula, and the Autonomous Regions of Azores and Madeira, two archipelagos in the Atlantic Ocean.

There are currently 24 radiotherapy (RT) centres equipped with 55 treatment machines including 52 linear accelerators, one Tomotherapy, one Cyberknife and one Gamma Knife. Eight out of these 24 centres are public institutions, having 29 treatment units.

Apart from the traditional beam output check auditing, usually followed by the reference hospitals, Portugal was one of the countries in the European region that embraced the challenge to carry out the first “end-to-end” dosimetry audit on TPS for 3D conformal radiotherapy (3D-CRT), after the methodology developed by the IAEA [1]. During 2011-2012, all 24 RT centres volunteered to participate in this national project [2].

The overall results suggested that the national status of TPS calculations and dose delivery for 3D conformal radiotherapy was globally positive with no major causes for concern.

This first ‘end-to-end’ audit contributed to the strengthening of the cooperation between all centres and medical physics professionals in Portugal, paving the way to further national collaborations.

That was the case when a new methodology developed by the IAEA and applied to IMRT was provided [3]. The CIRS Shoulder, Head and Neck End-to-End verification phantom



Fig. 1. Medical physicists positioning the CIRS thorax phantom during the “end-to-end” TPS dosimetry audit.



Fig. 2. Auditing team receiving the SHANE phantom for the IMRT audit.

– SHANE – simulating a head and neck (H&N) IMRT patient was the basis for this audit project. Currently, patients treated with IMRT represent approx. 1/3 of the total number of patients treated per year with external beam RT in the country, meaning that 3D-CRT is still the most frequently used treatment technique. Nevertheless, all centres using IMRT – 20 out of 24 – again voluntarily joined the new project, which successfully ran between March and September 2018.

Overall, the audit results showed that the status of TPS calculations and delivery for H&N IMRT in Portugal are within the specified tolerances. At the same time the audit identified factors that contributed to increased uncertainties in the IMRT dose delivery in some institutions, and the relevant recommendations for quality improvements were made.

The national strategy to finance both national audit projects was to organize kick-off workshops with interesting scientific programmes which attracted medical physicists and dosimetrists from all centres in Portugal and technical exhibitions whose promoters also contributed to the project budgets.

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QUATRO: Quality Assurance Team for Radiation Oncology

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The IAEA has a long tradition in dosimetry audits and contributed to improving the quality of radiotherapy across the globe [1]. While accurate radiation dosimetry is a critical requirement for radiotherapy quality, multiple other components in the radiation treatment chain must also be appropriate and of high quality. In view of the IAEA's contribution to quality radiotherapy over many years, requests were received to conduct clinical audits in radiotherapy. In response, the IAEA set up an expert group comprised of radiation oncologists, medical physicists and radiation therapists (RTTs), to prepare guidelines for comprehensive audits of radiotherapy practices called Quality Assurance Team for Radiation Oncology (QUATRO). The guidelines describe how to initiate, perform and report on the findings of comprehensive clinical audits [2].

QUATRO audits assemble teams of professionals (radiation oncologist, medical physicist, RTT) to peer review radiotherapy practices at radiation oncology centres with the aim to improve quality.

The QUATRO methodology incorporates a predefined audit structure and facilitates a standardized approach to the review of the audited centre's infrastructure, patient and equipment related procedures, quality assurance and safety programmes, as well as professional training programmes. QUATRO audits result in a series of recommendations for quality improvement and assist radiotherapy centres achieve the best level of practice possible in their economic settings.

Audits are voluntary and are only carried out at the invitation of the centre, with endorsement by the relevant governmental body. To date, QUATRO has conducted 99 audits in radiotherapy centres in the Central and Eastern Europe, Asia, Africa, and Latin America. Participating countries are marked in Figure 1.

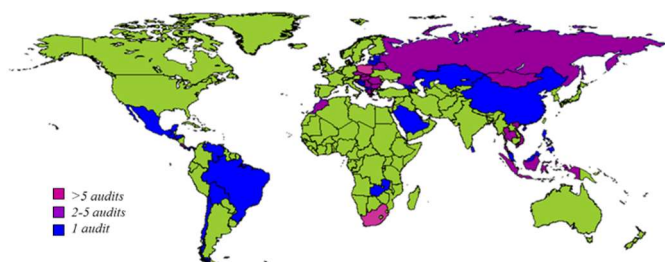


Fig. 1. QUATRO audits in 2004–2018.

Analysis of QUATRO findings was conducted based on a subset of reports from the audits in Europe [3] and Latin America [4]. In Europe, positive attributes of the audited centres included patient centredness, good communication, high quality facilities (with the marked exception of the insufficient availability of treatment machines) and physics quality control. Areas for improvement included staff numbers and equipment levels, professional development, documentation and quality management. In Latin America, recommendations to the audited centres were related to personnel, infrastructure, processes and institutional organizational aspects. Many recommendations warned governments about the need for allocating more budgetary resources to radiotherapy. Most recommendations pointed out to different aspects related to the training of local staff and to the need for technological support to audited centres.

Overall, QUATRO audits have contributed to significant improvements at the participating centres, and to identifying common issues of concern that are being addressed internationally.

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Multiple IAEA staff members and numerous experts have participated in the development, testing and implementation of the QUATRO audit methodology. Pedro Andreo deserves special mention for his ideas leading to the consolidation of medical physics and radiation oncology aspects of quality audits in radiotherapy and for his support at the beginnings of the development of QUATRO.

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