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The Largest Dosimetry Audit Organizations Worldwide

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ABSTRACT

Radiotherapy, also known as radiation therapy, is a treatment modality based on the use of high energy photon and electron beams to damage tumoral cells. It is used alone or in association with different treatments as an effective tool for treating cancer for more than 100 years. Safe and effective radiotherapy delivery requires the implementation of adapted quality assurance (QA) programs and integral quality management (QM) systems for the continuous quality improvement. A key step in any dosimetry QA program is the dosimetry audit, typically developed and organized by recognized independent external bodies. All beams used to treat cancer patients should be verified by an independent national, regional or international auditing organization. This is particularly important as radiotherapy is potentially a high-risk procedure. One of the risks for a patient undergoing radiation treatment, is that inadequate clinical dosimetry will have an impact on the local tumour control, treatment morbidity and toxicity and affects patient survival and quality of their life. Dosimetry audits have always been recognized as being important in radiotherapy (RT), providing an effective tool to improve the accuracy of patient treatments. In the global panorama, dosimetry audit programs have been conducted by various institutions, first of all the International Atomic Energy Agency (IAEA) in Vienna, Austria, Imaging and Radiation Oncology Core (IROC) Houston QA Center in USA and EQUAL (European Quality Laboratory) Laboratory in the framework of the ESTRO (European Society for Therapeutic Radiology and Oncology) ESTRO – EQUAL Laboratory in Villejuif Cedex, France.

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I will review the dosimetry audits of radiation therapy organized by world wide leading centers in terms of methods, tools and checked beams. the review is based on documentary method – systematization and analysis of information from international and world contemporary literary sources.

Dosimetry audit organized by International Atomic Energy Agency (IAEA)

In 1969, the IAEA and WHO launched the project known as the IAEA/WHO TLD postal dose audit program [1-6]. The motive of the program is to improve the accuracy and traceability of dosimetric measurements in clinical dosimetry used for radiation therapy purposes in therapeutic centers around the world. 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 interhospital 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.

Since 1981, the program has also audited Secondary Standard Dosimetry Laboratories (SSDLs) in order to achieve traceability and repeatability in dosimetry measurements anywhere in the world. The program was originally developed for cobalt therapy machines, but since 1991 has also included audits of high-energy X-rays generated by clinical accelerators.

The postal dose audit program is a collaboration between the IAEA and the WHO. WHO is responsible for coordinating the distribution of dosimeters, while the IAEA is responsible for the technical aspects of the TLD program, which includes the evaluation of the results of dosimetric measurements perfoming in Dosimetry Laboratory situated in complex of Nuclear Applications Laboratories in Seibersdorf near to Vienna, Austria.

Today IAEA dosimetry audit service covers radiotherapy centers in East Europe, Africa and South America is shown in Figure 1 [7].

Figure 1: Geographical Region Coverage by the Dosimetry Audit Organized by IAEA [7].

The dosimetry audit program is organized in 9 cycles per year. Every two years, each participating radiotherapy center can participate in one of these audit cycles. A set of dosimeters is provided only to those institutions that agree to the conditions of the dosimetric audit organized and conducted by the IAEA/WHO.

During the cycles of dosimetry audits is strictly defined time interval, called the "irradiation window". In that time the IAEA dosimetry laboratory irradiates the so-called reference dosimeters with γ-rays of Co-60 with a dose of 2Gy. The number of reference dosimeters corresponds to the number of beams to be checked. Therefore, it is important that participants adhere to the fixed exposure window. In every each irradiation cycle, two reference institutions, such as SSDL and leading radiotherapy centers, which are members of the group of Affiliated Members of the IAEA/WHO Network of SSDLs, irradiate dosimeters with precisely defined doses to ensure the necessary quality control of the dosimetry process in the IAEA Dosimetry Laboratory.

For the purposes of the audit as a detector a powdered TLD material LiF(Mg, Ti), type TLD-100 (Harshaw) was initially used. The calibration of the thermoluminescent dosimetry system includes the determination of a calibration factor, a nonlinearity factor, and a signal attenuation factor (fading). Irradiation of the reference dosimeters is performed by placing the capsules at a depth of 5 cm in a 30x30x30 cm solid water phantom. Three capsules are irradiated simultaneously. The phantom is shown in Figure 2.

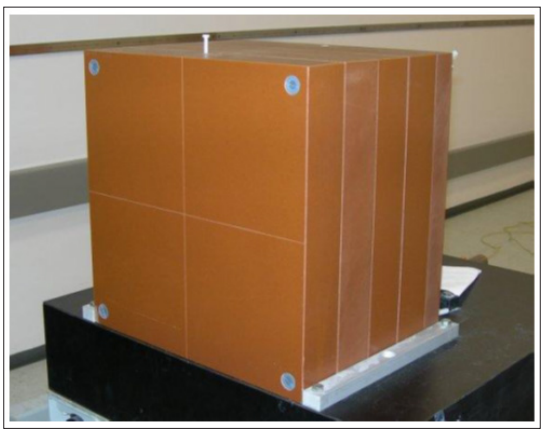

Figure 2: IAEA phantom made of so-called solid water (solid state phantom) for irradiation of capsules [7].

The reading of the dosimeters in the IAEA laboratory is carried out with an automatic TLD analyzer - PCL3 (Fimel, France) shown in Figure 3.

Figure 3: Automatic TLD Analyzer - PCL3 (Fimel, France) used to determine the readings of irradiated thermoluminescent dosimeters-TLDs in the IAEA Dosimetry Laboratory [7]

The results of dosimetry audits with TLDs organized in the period 1969-2003 in Eastern and South-Eastern Europe and Latin America have been discussed and published, as well as the results worldwide in 1998-2007 [1-6].

The participant in the program (Radiotherapy Center) receives a data sheet that must be filled out. The information provided should include the method used to determine the ingested dose, facilitating investigation in the event of an unacceptable result. The radiotherapy center must irradiate two TLD dosimeters sequentially with a dose of 2 Gy in water under the following reference conditions: field dimensions S = 10 x 10 cm, depth 10 cm in water at nominal source-to-surface distance (SSD) or at the distance between the source and isocenter (SAD) used in clinical settings at the particular radiotherapy center. In addition to the dosimeters that must be irradiated in the relevant center, a control capsule which is marked in white color. This dosimeter is used to record possible environmental influences during the transport and storage of TLDs. A set of TLDs is shown in Figure 4.

Figure 4: A set of TLDs that contains two dosimeters and one control dosimeter (marked in white) to detect environmental influences and storage of the dosimeters. The dosimeter consists of LiF powder, with the plastic capsules are filled [7]

Participating member laboratories of the SSDLs network are required to irradiate three TLD dosimeters under reference conditions. During the irradiation, the dosimeters are placed in a specially prepared plastic holder, which is provided by the IAEA. The holder is shown in Figure 5.

Figure 5: Special plastic holder for TLD Dosimeters [7]

Treatment facilities that regularly participate in the program show better results than those that participate for the first time. Analysis of results from recent years shows that the percentage of centers that participate for the first time and have results within the accepted limits of deviation is 78%, while 90% of regularly participating centers have acceptable results [1-5].

Dosimeters irradiated by participants with a dose of 2Gy must arrive at the IAEA laboratory no later than 6 weeks after their exposure. Audit results are sent to participants within 8 weeks of receiving their radiation dosimeters at the IAEA. Participants receive individual certificates with the result of the inspection of each individual beam. Results are defined as the ratio Diaea-Dstat/ Diaea x 100%, and are considered acceptable if within ± 5% [1].

The maximum permissible discrepancy between the dose indicated by the audited clinical center and the dose determined by the IAEA is ±5%. In the event that the discrepancy is greater, an additional audit is performed. If the second audit also shows a deviation greater than the limit, the center receives assistance from the IAEA to resolve the problem. For SSDL, the accepted deviation is ± 3.5% [7].

In 2017, the IAEA Dosimetry Laboratory upgraded its laboratory equipment with a new radiophotoluminescent dosimetry system (RPLDs) using glass dosimeters. As a result, the IAEA/WHO Postal Dose Audit Program is now known as the IAEA/WHO Postal Dose Audit RPLD Programme [8].

The new Dose Ace system consisting of GD-302M glass rods and a FDG1000 reader from Asahi Techno Glass Corporation (ATG) is used in IAEA Dosimetry Laboratory. /See Figure 6/

Figure 6: Dose Ace system consisting of GD-302M glass rods and a FDG1000 reader from Asahi Techno Glass Corporation (ATG) [7]

The glass rods are made of silver activated phosphate glass; they are 12 mm long and 1.5 mm in diameter, with an ID number engraved on one end. The sensitive area of a dosimeter is 6 mm long. RPLDs are encapsulated in custom made watertight capsules. Each capsule has an ID number and a bar code. The sensitive area is also marked on the capsule to allow precise positioning. /See Figure 7/.

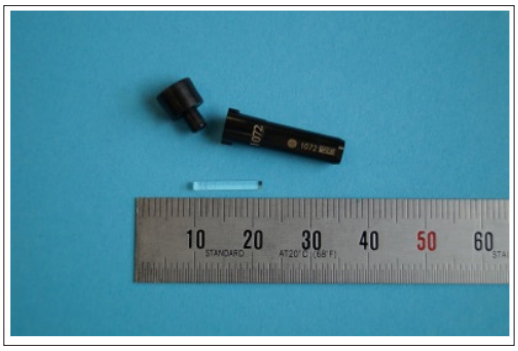

Figure 7: RPLD dosimeter and watertight capsule [8]

The FGD-1000 reader can read up to 20 glass rods in a session of 5 min. After irradiation, the dosimeters are kept in a low humidity storage cabinet for 24 h and are then preheated to 70º C to stabilize the luminescence centers. RPLDs can be read several times as the read out process is not destructive.

The IAEA, together with the World Health Organization, has organized the Postal Dosimetry Audit Program to improve the accuracy and consistency of reference dosimetry in radiation therapy centers worldwide for more than 50 years. 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 [9].

In the five decades since the creation of the program until 2018, 2,364 radiation therapy centers in 136 countries have been audited. 4427 radiation therapy devices generating 5790 photon beams were tested and 13756 results were obtained. On average, 86% of audit results are within ±5% tolerance [10].

The distribution of audit results presented as Dm/Ds ratios of the IAEA measured dose (Dm) and the dose indicated by the inspected center (Ds) for the period 1969-2018 is shown in Figure 8.

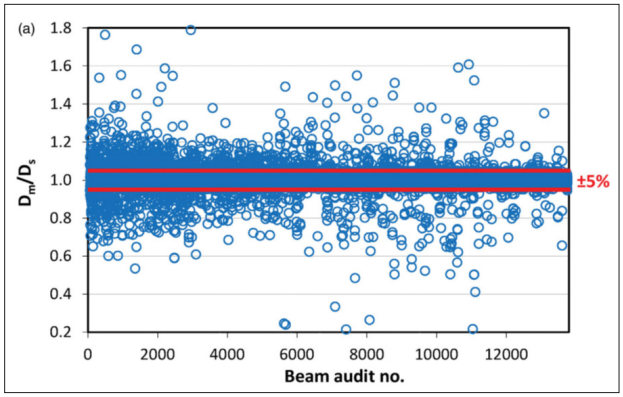

Figure 8: Results of a dosimetry audit conducted by the IAEA/WHO in the period 1969-2018. 13,756 audits of photon beams generated by 4,427 radiotherapy devices in 2,364 radiotherapy centers from 135 IAEA member states [10]

Since June 2021 IAEA/WHO postal audits service has been expanded to include electron beams. The methodology is developed in IAEA Dosimetry Laboratory including the use of a laboratory-made holder system to position dosimeters at the reference depth, the measurement of all relevant correction factors for the determination of absorbed dose, and multi-center testing of the methodology. The new audit service is available for radiotherapy departments in Member States [11].

Dosimetry Audit organized by Imaging and Radiation Oncology Core (IROC) Houston QA Center

Imaging and Radiation Oncology Core (IROC) Quality Assurance Center is an organization based in Houston, Texas. It has the largest dosimetry program in the world and audits all radiation therapy centers in the United States.

The beginnings of dosimetry audit to verify beam calibration under reference conditions began at the Radiologic Physics Center (RPC at that time) in 1968. The Remote Dosimetry Audit Program was established based on mailable detectors. The dosimeters shoul be irradiated under conditions of elementary geometry, to preserve the dosimetric signal after irradiation and to be able to be read in a reproducible manner.

The geographical region coverage by the dosimetry audit services of IROC – Houston includes all radiotherapy centers in USA and some countries in South America, Africa and Australia is shown on the Figure 9.

Figure 9: Geographical region coverage by the dosimetry audit organized by IROC [7]

The IROC-Houston thermoluminescence dosimetry system is based on TLD-100 detectors (LiF: Mg, Ti) distributed in cylindrical Teflon capsules. The mass of thermoluminescent powder in each capsule is about 20 - 22 mg. Measurement of absorbed dose from TLDs was performed with a Harshaw Model 3500 TLD Analyzer (Thermo Scientific, Waltham MA). /See Figure 10/ Thermoluminescence dosimetry has been used for decades, as previously been introduced by Kirby et al. [12-14].

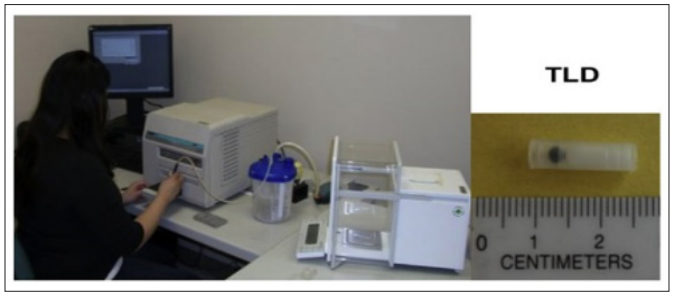

Figure 10: The remote dosimetry audit with thermoluminescent dosimeters-TLDs in IROC-Houston [12]

Remote dosimetry audit is mandatory for all radiation therapy centers participating in National Cancer Institute (NCI)-sponsored clinical trials, both in the US and internationally [15,16]. The goal is to assure NCI that institutions participating in clinical trials and members of the National Clinical Trials Network (NCTN) implement prescribed radiation doses that are clinically comparable, traceable, and consistent. IROC-Houston provides an integrated quality control program in radiation therapy and imaging in support of the NCTN network and the NCI, thereby providing high-quality data for ongoing clinical trials designed to improve treatment outcomes for cancer patients worldwide. Since 1982 electron beams for radiotherapy were also included in remote dosimetry audit. The beginning of the remote dosimetric audit of proton beams used for the clinical purposes of radiotherapy was set in 2007 [12,17,18].

Since 2010 part of the remote dosimetric audit is based on the use of optically stimulated luminescent dosimeters (OSLD), which replaces the use of TLDs for photon and electron beams [17-19]. The optically stimulated luminescence dosimeters (OSLD) nanoDot (Landauer Inc., Glenwood Il) are used. The measurement of the dosimeters is carried out by the Landauer MicroStar InLight analyzer. Three consecutive 7-seconds in long readings are obtained for each dosimeter. /See Figure 11/.

Figure 11: The remote dosimetry audit with OSLD nanoDot (optically stimulated luminescent dosimeters) in IROC-Houston [12]

OSLDs are subjected to special heat treatment/preheating before to use and can be used repeatedly up to a total cumulative dose of 10 Gy (after which the sensitivity of the detector begins to change dramatically. The preheating process is performed with a specially designed light phantom [17-21].

Both types of TLD and OSLD dosimeters are calibrated to determine the absorbed dose for photon and electron beams of energies used in radiation therapy. An acrylic mini-phantom is used to calibrate the reference dosimeters under reference geometry conditions that are irradiated with γ rays of the radionuclide Co-60. The realized dose is D=300cGy for TLDs and D=100cGy for OSLD. The dose for OSLD is lower to increase the number of irradiation cycles of each detector before reaching a cumulative dose of 10 Gy. Both TLDs and OSLD systems are designed to be used under very stringent exposure and measurement conditions. These dosimeters have proven to be robust and suitable for conducting remote dosimetry audits. The OSLD dosimetric system has a much shorter reading process and better performance. The irradiation geometry for both types of dosimeters (TLD and OSLD) is analogous: The reference conditions defined by the dosimetry protocols, i.e. distance source - surface 100 cm and size of the radiation field S = 10 cm × 10 cm, depth of dose realization d = 10 cm.

The dosimetry audit program is constantly growing. In 2015, over 2,100 institutions were audited and more than 22,600 beams were inspected, making the program the largest in the world. Over 16 000 results were obtained with TLD dosimetry and more than 4 200 results with OSLD dosimetry. The mean of the dose ratio Dmeas/Dstat at the check point was 1.000 ± 1.9% for TLD and 0.999 ± 1.7% for OSLD. The results of more than 20 000 dose measurements under reference conditions are shown in the figure. /See Figure 12/ Of more than 20 000 measurements, only 2.4% were outside of the 5% tolerance established by IROC-Houston.

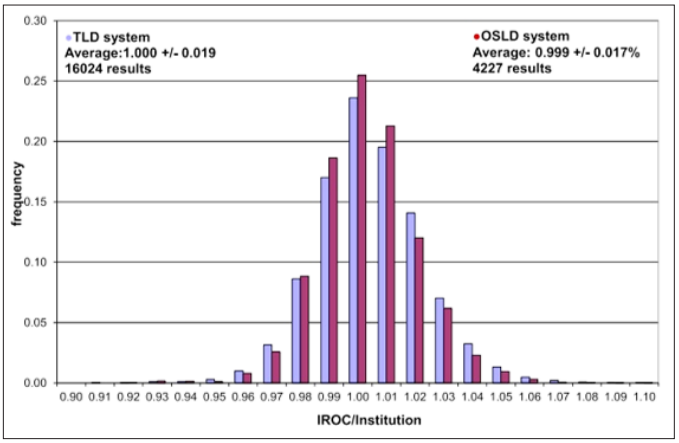

Figure 12: 20,000 Remote Dosimetry Audit results at IROC-Houston obtained by measurements with thermoluminescent dosimeters-TLDs and OSLD nanoDot -optically stimulated luminescent dosimeters [12]

Dosimetry Audit organized by ESTRO – EQUAL Laboratory

The Center for Dosimetry Measurements is located in the Medical Physics Department of the Institut Gustave-Roussy (IGR, Villejuif, France). The idea of creating the dosimetry laboratory at the European Society for Radiotherapy and Oncology (ESTRO), known as the European QUALity assurance network (EQUAL), arose at the end of 1997 [22].

EQUAL's program mainly includes the member states of the European Union, and Switzerland. In our days the region overeager by the dosimetry audit service offered by the EQUAL is shown in the Figure 13.

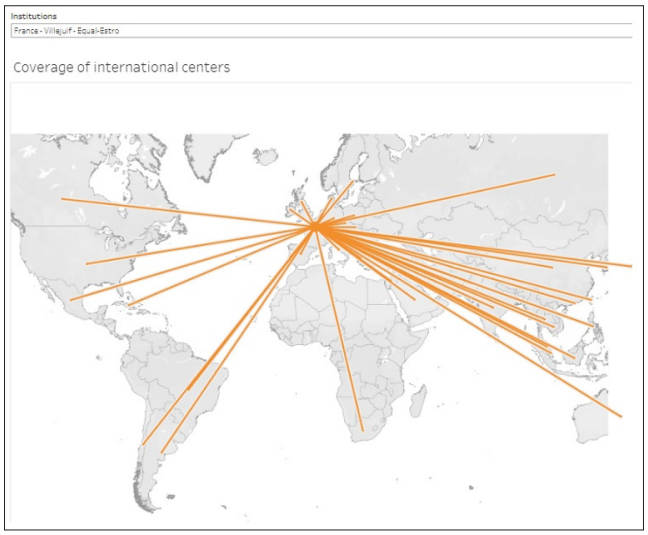

Figure 13: The region covereg by the dosimetry audit service offered by ESTRO-EQUAL Laboratory [7]

The first postal dosimetry audit was conducted in 1998. The maximum number of photon beams for each participant (radiotherapy center) was determined to be 3 /three/. The dosimetric method used is based on thermoluminescence dosimetry. /See Fig. 14/ LiF enriched with Na, Mg and Ti in powder form, produced by DTL 937 (Philitech Company, Buc, France) was used for TL material and an automatic analyzer Fimel, VeÂlizy, France for the analyzer of the thermoluminescent dosimeters [23-26].

The methodology in terms of organization practice is based on postal dosimetry audit. The dosimeters are mailed to the participant, along with the holder and the package of documentation. Dosimeters should be irradiated in a water phantom at a fixed source-surface distance (SSD) or source-isocenter distance (SAD) depending on what is used in local clinical practice. To realize the required absorbed dose, each participant in the audit must irradiate the dosimeters with the necessary monitoring units.

The checked dosimetry quantities are:

- Dose in reference conditions
- Percent depth dose
- Variation in the dose value in reference conditions with a change of the field size
- Wedge factor

In 2002 the laboratory launched a new dosimetry audit, allowing verification of dosimetry quantities and parameters characterizing complex radiotherapy fields modified by a multi-leaf collimator. A dosimetry audit was also introduced to control physical quantities characteristing of brachytherapy. Until 2003 the activity of the laboratory is financed through European projects. In 2004 the Equal - ESTRO laboratory is accredited [27,28].

From the very beginning, the laboratory demonstrated great activity. In the conducted dosimetry audits, 46% of France's radiation therapy centers were covered. 55% of the European centers declare their willingness and readiness to participate in the audits organized by the laboratory [24]. A mandatory part of a dosimetric audit program is verification of the calibration under

reference conditions of the photon and electron beams used for radiation therapy.

Figure 14: Thermoluminescence dosimetry at the Equal - ESTRO laboratory used for remote dosimetry audit purposes [22]

More than 9,000 therapeutic photon and electron beams have been verified through this remote dosimetry audit [24-26]. Acceptability criteria for TLD measurements correspond to a maximum allowable dose deviation of ±5%.

Dose checks in reference conditions with thermoluminescence dosimetry of the photon and electron beams used for radiotherapy in France show that more than 90% of the beams have a deviation within 1% and only one accelerator has a deviation between 3 and 5% [27].

Over the past 10 years, with other national and international audit organizations, the EQUAL-ESTRO laboratory has developed and provided new methodologies for dosimetric audits in modern radiotherapy, including new dose delivery techniques such as IMRT, VMAT, Tomotherapy and CyberKnife [28-30].

After 2010, film dosimetry was introduced. For the film measurements, films with a special chemical composition GafchromicTM EBT3 (Ashland Specialty Ingredients, Bridgewater, NJ, USA) are used. Film analysis was performed using an Epson® Expression® 10000XL scanner. The comparison of the dosimetric distribution between films and radiotherapy plans is analyzed using a special software - IMRT QA software, OmniPro I'mRT (IBA Dosimetry). Dosimetric audit based on film dosimetry is used to assess the 2D dose distribution. For this purpose, a water-equivalent geometric phantom is used, in which inhomogeneities have been added regarding the lung and bone tissues. The phantom allows the positioning of films in the axial, coronal and sagittal orientations up to 16 cm x 16 cm in size. /See Figure 15/

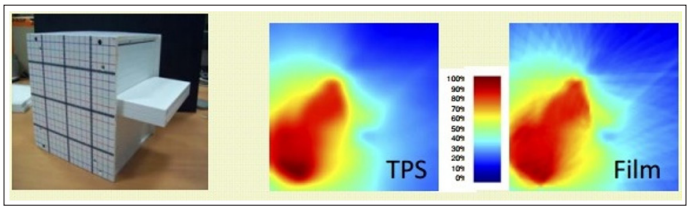

Figure 15: Film dosimetry in the Equal - ESTRO laboratory used for remote dosimetry audit purposes [22]

In the period 2014 - 2018, an end-to-end dosimetric audit was developed to check tomotherapy equipment with a specially designed phantom [22,28-30]. The audited center receives the phantom along with the CT images needed to prepare the radiotherapy plan. Planning and irradiation of the phantom must be performed at the audited center according to the protocols used at the center. The only limitation imposed by the EQUAL-ESTRO laboratory is that the maximum prescribed dose be no higher than 8 Gy. A total of 43 dosimetry audits were carried out, with some of the radiotherapy equipment being checked more than once.

In the same period, the results of measurements performed with TLDs in the EQUAL-ESTRO laboratory were extremely satisfactory, as no deviation above ±5% was detected. The results of the film dosimetric audit are also very good, as in 98% of cases the requirements of the gamma criterion for distance and dose/γ index, 2D global gamma passing rates with a gamma criterion of 5%/3 mm are met.

The 2D film images are compared to the radiotherapy plans by the planning systems, taking into account the accepted eligibility criteria as follows:

- 2D film images - Dose deviation must be less than 10% for at least 90% of the film surface
- The gamma test for dosimetric comparison should be 5%/3 mm as the result of 5% of the dose value should be higher than 90% for the audited centers.

Film measurements have shown acceptable results for all tests performed. For more than 70% of the radiotherapy plans audited, the criteria for gamma test coverage rate was higher than 95%.

Discussion

At present time over 8 000 radiotherapy centres in 150 countries worldwide are registered in the IAEA Directory of Radiotherapy Centres (DIRAC) [31]. They operate approximately more then 15 000 radiotherapy machines using in modern radiotherapy to treat cancer patients. In nowadays some high-income countries as North America, Japan, Australia and a several European countires (e.g. Belgium, Czech Republic, Finland, France, Greece, Germany, the Netherlands, Norway, Poland, Slovakia, Switzerland and UK) have good dosimetry audit coverage [32].

The largest organizations, the IAEA jointly with the World Health Organization (WHO), the Imaging and Radiation Oncology Core (IROC) Houston QA Centre (former Radiological Physics Centre) together with the Radiation Dosimetry Service (RDS) also based in Houston, USA, and the EQUAL-ESTRO, Villejuif, France, reported extending their services to an inter-continental level where annually, the IAEA delivers audits to radiotherapy centres in 60–70 countries, IROC-Houston and RDS to about 60 countries, and EQUAL-ESTRO to about 40 countries [7,12,22].

Conclusion

Better availability of the dosimetry audit is necessary for improving dosimetry practices in radiotherapy and also in order to increase the safety of patients undergoing radiation treatments. The dosimetry audit is organized worldwide for the purpose of enhancing confidence in the accuracy of clinical dosimetry and ensuring that the facility QA procedures are adequate. The value of independent dosimetry audit is now better recognized and has become well documented. From the excellent work of the IAEA and national standards labs in reference dosimetry audit through

to end-to-end measurements which follow the commissioning of a new advanced radiotherapy technique, there is no doubt that the quality of radiotherapy has improved over recent decades, and that audit has played a role in this [33]. The dosimetry 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.

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