ACTA ONCOLOGICA, 2016
VOL. 55, NO. 7, 909–916
http://dx.doi.org/10.3109/0284186X.2016.1139180

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ORIGINAL ARTICLE

Testing the methodology for dosimetry audit of heterogeneity corrections and small MLC-shaped fields: Results of IAEA multi-center studies

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ABSTRACT

The International Atomic Energy Agency (IAEA) has a long tradition of supporting development of methodologies for national networks providing quality audits in radiotherapy. A series of co-ordinated research projects (CRPs) has been conducted by the IAEA since 1995 assisting national external audit groups developing national audit programs. The CRP 'Development of Quality Audits for Radiotherapy Dosimetry for Complex Treatment Techniques' was conducted in 2009–2012 as an extension of previously developed audit programs. *Material and methods.* The CRP work described in this paper focused on developing and testing two steps of dosimetry audit: verification of heterogeneity corrections, and treatment planning system (TPS) modeling of small MLC fields, which are important for the initial stages of complex radiation treatments, such as IMRT. The project involved development of a new solid slab phantom with heterogeneities containing special measurement inserts for thermoluminescent dosimeters (TLD) and radiochromic films. The phantom and the audit methodology has been developed at the IAEA and tested in multi-center studies involving the CRP participants. *Results.* The results of multi-center testing of methodology for two steps of dosimetry audit show that the design of audit procedures is adequate and the methodology is feasible for meeting the audit objectives. A total of 97% TLD results in heterogeneity situations obtained in the study were within 3% and all results within 5% agreement with the TPS predicted doses. In contrast, only 64% small beam profiles were within 3 mm agreement between the TPS calculated and film measured doses. Film dosimetry results have highlighted some limitations in TPS modeling of small beam profiles in the direction of MLC leave movements. *Discussion.* Through multi-center testing, any challenges or difficulties in the proposed audit methodology were identified, and the methodology improved. Using the experience of these studies, the participants could incorporate the auditing procedures in their national programs.

ARTICLE HISTORY
Received 21 October 2015
Revised 22 December 2015
Accepted 31 December 2015
Published online
26 February 2016

For several years the number of cancer cases has been growing steadily across the world [1] and this has prompted many governments to invest in cancer control programs which include, among other things, the installation of radiotherapy equipment. Furthermore, through national cancer programs and international initiatives, such as the IAEA's Technical Cooperation (TC) Program, access to more complex radiotherapy treatment techniques has spread to low and middle income (LMI) countries. According to the IAEA hosted Directory of Radiotherapy Centers (DIRAC) [2] from all radiotherapy machines registered worldwide, 82% are linear accelerators. There is also a substantial increase in the number of machines capable of delivering complex treatments, such as stereotactic radiotherapy (SRT) and intensity-modulated radiotherapy (IMRT), in LMI countries. However, these developments have not been accompanied by a corresponding ability to audit complex radiation treatment techniques in these countries.

During the last decades the IAEA established a framework for operating national audit networks for radiotherapy dosimetry in LMI countries and developed methodology and procedures for postal beam dosimetry checks through a series of three co-ordinated research projects (CRPs) [3–5]. Postal audits play an important role as on-site audits are not easy to implement because of various constraints including lack of trained personnel. These CRPs have resulted in guidelines on how to structure and operate national external audit groups (EAGs) [3], which require involvement and collaboration of clinical radiotherapy medical physicists with staff from national standards dosimetry laboratories. Participation in multi-center exercises within the IAEA CRPs

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enables the EAGs to build confidence in introducing audits for more complex technologies and treatments at the national level. The methods and tools developed and described within these CRPs are adapted by national audit networks to suit local situations.

Since the beginning of the CRPs, six steps of dosimetric audits have been developed for the increasing complexity of dose calculation and delivery, where each audited hospital must successfully complete the preceding audit step before participating in a subsequent one. Step 1 addresses beam output in reference conditions, Step 2 involves the dose determination in non-reference conditions on-axis, Step 3 covers dose determination in non-reference conditions off-axis for open and wedged fields, and Step 4 audits irregular fields shaped with an MLC. The first four steps in the audit programs have been described previously [4–6].

In order to address the need for remote audits in LMI countries with respect to more complex radiotherapy techniques, additional steps of this dosimetry audit program have been developed and tested in a pilot study in 2009–2012. More specifically, the audit Step 5 aims at the dose verification for high energy photon beams in the presence of heterogeneities in the body composition, which is particularly relevant for lung but also applicable to bone. The audit Step 6 verifies the modeling of small MLC-shaped fields as both the magnitude of the dose and the shape and localization of the beam profile are important, especially for SRT and IMRT. Steps 5 and 6 focus on verifying treatment planning system (TPS) calculations for the beam parameters that are more closely related to clinical treatments than previous audits Steps 1–4 and involve significant testing of clinical systems, and as such require more involvement of clinical radiotherapy physicists in the EAG teams.

The current paper presents the methodology testing for the audit Steps 5 and 6, verifying heterogeneity corrections and checking small MLC-shaped beam profiles including a description of the phantom development for carrying out these remote dosimetry audits, as well as results obtained in two multi-center studies for these audit steps. The participants in this CRP were EAGs from Algeria, Argentina, Brazil, China, the Czech Republic and Poland. Other participants from Austria, UK and USA served as consultants involved in the development of audit methodology and its pilot testing.

Materials and methods

Overview

Following the development of a dosimetry audit program framework, for each step in the audit, a dosimetry phantom and a specific set of documentation was developed both for EAGs and for hospitals that will take part in the national audits at a later stage. Written instructions describing the audit methodology, data sheets for reporting irradiation details by participants and also guidelines for the EAGs for dosimeter preparation, handling and evaluation as well as reporting of the audit results were developed. Next, a multi-center pilot study involving all CRP participants was performed with the purpose of testing and validating the newly developed methodology and audit procedures, including the clarity of the technical documentation. This way any potential ambiguities or inconsistencies in the audit methodology and procedures could be detected and rectified before the methodology is tested and implemented at the national level. The analysis of dosimeters used in multi-center pilot studies was performed by the IAEA Dosimetry Laboratory. Following the multi-center study, the audit methodology has been subsequently tested locally with 3–5 hospitals and the dosimeter evaluation was performed by the EAGs. This way the methodology was validated and adjusted to the local circumstances, and the national audits could be provided for all hospitals in the country interested to participate.

In the multi-center study, thermoluminescent dosimeters (TLDs) were used for the dose measurements. The TLDs consisted of TLD-100 powder (Harshaw, USA) encapsulated in plastic capsules of 2.5 cm length with 0.5 cm diameter, with the inner dimensions of 1.9 cm length and 0.3 cm diameter. TLDs were analyzed in accordance to the standard IAEA protocol [7]. The uncertainty in the TLD measurements was 1.8% (1 standard deviation). For dose profile measurements Gafchromic EBT2 films were used. Irradiated films were scanned with an EPSON 4990 flat-bed scanner (EPSON, Japan) in a portrait orientation using the transmission mode, 72 dpi resolution and 48 bit RGB scale. FilmQA Pro (Ashland, USA) software was used to obtain dose distributions from the films using a triple channel method. The estimated uncertainty in the film dosimetry was 1.6% (1 standard deviation).

Step 5 – TLD quality audit for photon beams in the presence of heterogeneities

The purpose of this audit step is to verify the accuracy of dose calculation performed by the clinically used TPS in the presence of heterogeneities using TLDs. A small phantom measuring $15 \times 15 \times 15\,cm^3$ with bone and lung equivalent material inserts was designed and manufactured. The size of the phantom ensured sufficient scatter conditions for the field sizes used in the audit program. The phantom was made of polystyrene (density of 1.04 g/cm^3) and the heterogeneity inserts were made of Hydex (density of 1.31 g/cm^3) and cork (density of 0.24 g/cm^3) to simulate bone and lung, respectively. The phantom can be configured in different ways depending on the irradiation conditions required; Figure 1 shows the three configurations used in this audit step and the location of TLD positions for each phantom configuration.

Participants were requested to provide a computed tomography (CT) scan of the phantom in three configurations using imaging protocols they normally use for patients. Next, the images were exported to the TPS, and the dose calculations were performed with the clinically used dose calculation methods to deliver 2 Gy to the TLD at 10 cm depth for a $6 \times 6\,cm^2$ field size under SSD or SAD conditions, with the energy most often used for thorax treatments at the participating center. Six participants chose 6 MV beams, two 10 MV and one 4 MV beam. The participants were asked to contour TLDs for planning and report the dose at the center of TLD capsule for each TLD position. The following TPS and algorithms, respectively, were used: (1) Varian Eclipse (pencil beam convolution, modified Batho power law and anisotropic

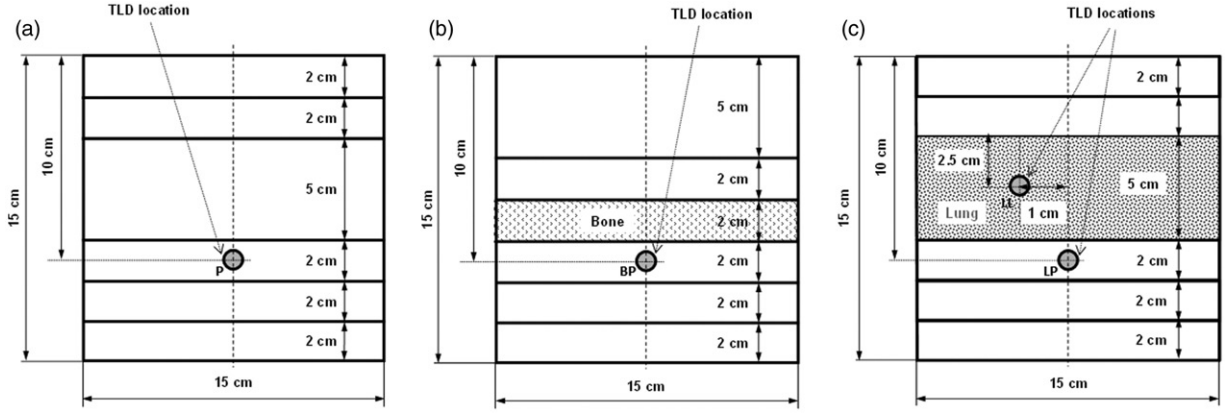


Figure 1. Cross sections of the three configurations of the phantom showing location of TLDs; (a) homogeneous polystyrene phantom indicating P position, (b) polystyrene phantom with bone material indicating BP position and (c) polystyrene phantom with lung material indicating two TLD positions LL and LP.

analytical algorithm AAA); (2) Elekta/CMS XiO (superposition); (3) Philips Pinnacle (collapsed cone superposition/convolution); and (4) Oncentra MasterPlan from Elekta (enhanced collapsed cone convolution). The detailed descriptions of the algorithms can be found in literature [8,9]. Two TLDs were irradiated at each position in the phantom, points P, BP, LP and LL, in three phantom configurations as it can be seen in Figure 1. The TLD results were reported as the ratio D_{TLD}/D_{stat} of the TLD determined dose, $D_{TLD,}$ to the dose stated by the participants, D_{stat}.

In order to reflect upon the actual clinical situation, TLD results were not corrected for the daily linac output fluctuations. However, for the audit methodology testing, the measurements of the linac output were performed before the TLD irradiation by participants in the multi-center study, to make sure all beams were within the clinically used tolerance levels.

In addition to irradiating TLDs following the audit protocol, three participants performed ionization chamber measurements using a special ionization chamber holder to obtain doses in the positions of TLDs in order to derive any applicable corrections for TLD readings.

Step 6 – quality audit for small photon MLC-shaped beam profiles

Small field dosimetry presents known challenges due to the interplay between the field dimensions, the detector size and material, and the loss of lateral charged particle equilibrium [8,10,11]. Beam modeling for small fields should be optimized in TPS algorithms in order to achieve good agreement with the measured beam parameters [12,13]. The purpose of this audit step was to check the dose profile calculations performed by TPS for small photon MLC-shaped fields as used for patient treatments. This was done by performing a simple comparison between the profiles generated by TPS and those obtained from film measurements. A set of TLDs were also irradiated at the same depth as the film to confirm that the correct dose was delivered to the film. This audit was an important first step in checking the basic beam modeling by TPS for small fields, as well as developing film dosimetry methodology for EAGs.

This audit was carried out using the polystyrene phantom described in Step 5 above with the phantom quipped with a dedicated film cassette. The slab with the drawer for TLDs shown in Figure 1(a) was replaced by a slab with a film cassette (see Supplementary Material, Supplementary Figure 1, available online at http://www.informahealthcare.com). The film was located at 10 cm depth for irradiation.

Eight hospitals associated with the national EAGs took part in the multi-center audit run to test the audit methodology. The participating centers were asked to scan the phantom, export CT images to TPS and calculate the dose distributions for a $2 \times 5\,cm^2$ and a $2 \times 2\,cm^2$ photon beams shaped with the MLC for a prescribed dose of 8 Gy at 10 cm depth on the central axis of the photon beam under SSD or SAD conditions, depending on their preferred clinical practice. In-plane and cross-plane dose profiles (through the central axis) in 1 mm resolution were generated from TPS calculations. Two films were irradiated with each beam using $2 \times 2\,cm^2$ and $2 \times 5\,cm^2$ fields. In addition to the film irradiation, a dose audit was also carried out by requesting the participants to irradiate TLDs with a dose of 2 Gy in the $2 \times 5\,cm^2$ field. The longitudinal axis of the TLD was placed perpendicular to the MLC leaf direction (see Supplementary Material, Supplementary Figure 1, available online at http://www.informahealthcare.com). The audit methodology suggested that the beams most often used clinically should be selected; however, within the pilot study a broader range of beam energies was tested. Participants performed irradiations using 14 high energy photon beams of 4 MV (one participant), 6 MV (eight participants), 10 MV (four participants) and 18 MV (one participant).

The irradiation of films by participants and irradiation of calibration films by the IAEA Dosimetry Laboratory was synchronized in time. A set of nine calibration films in the range of 0−9 Gy was irradiated in a solid water phantom at the reference conditions following the TRS 398 code of practice [14] for 6 MV and 10 MV beams. Both the calibration and the participants' films were scanned under the same conditions, about five weeks from the irradiation date. The calibration curves used for the analysis of participants' films irradiated with 4 MV and 18 MV were generated using the scaling factors determined following the methodology described by Richter et al. [15] applied to the calibration function for 6 MV. Comparison of calibration fitting functions showed very good agreement within the film calibration uncertainty.

The in-plane and cross-plane profiles for two field sizes were compared with those generated by the TPS. Profiles from film

and TPS were superimposed, normalized at the center of the field and the relative differences between the profiles at the 20%, 50% and 80% isodose levels were calculated.

The report to the participating center included the TLD delivered dose and the film profiles compared with the TPS data.

Results

Step 5 – TLD quality audit for photon beams in the presence of heterogeneities

Figure 2 shows the D_{TLD}/D_{stat} ratio of the TLD measured dose to the participant stated dose for the $6 \times 6\,cm^2$ field size for nine participating EAGs for all P, LP, LL and BP measurement points for all beam energies. Corrections for TLD readings that were determined from ion chamber measurements in the LL position were applied to account for differences in the TLD response in cork and polystyrene slabs of the phantom, simulating lung and normal tissue. They were in the range of 1.009–1.015 for the beams of 4–10 MV, respectively. TLD measurements in other points in the phantom did not require a correction. As can be seen in Figure 2, the participants' results of D_{TLD}/D_{stat} for all beams and all measurement points were within ±3%, except for the RC5 center using a 4 MV beam which had lower results, i.e. D_{TLD}/D_{stat}=0.96 for LP and D_{TLD}/D_{stat}=0.97 for LL points for the TLDs in the lung configuration (Figure 1c). Also the RC6 center had relatively lower ratio of D_{TLD}/D_{stat} for the LL TLDs. More information on the TLD results distribution parameters are given in the Supplementary Table 1 (available online at http://www.informahealthcare.com). Overall, based on the results of the multi-center study the acceptance limits of ±5% for the audits at the national level were considered feasible and these limits were recommended for testing within the national trial runs.

Step 6 – quality audit for small photon MLC-shaped beam profiles

Overall, the analysis of 28 films irradiated with 14 beams by participants was performed in order to derive beam profiles and compare them with TPS data. Figure 3 gives two examples of comparisons between the film measured and TPS calculated in-plane and MLC-shaped cross-plane beam profiles for a $2 \times 2\,cm^2$ field. The profile widths at 80%, 50% and 20% dose levels are also shown. Figure 3(a) and (b) illustrates good agreement between the TPS calculated and film measured beam profiles whereas Figure 3(c) and (d) gives an example of poor results.

The agreement at the 50% isodose level was within ±0.2 cm for all participating centers, all beams, for both $2 \times 2\,cm^2$ and $2 \times 5\,cm^2$ field sizes. However, this was not the case for 80% and 20% dose levels where greater discrepancies occurred, in particular for the MLC-shaped cross-plane profiles.

Figure 4(a) and (b) summarize the differences between the measured and calculated profile widths in-plane and cross-plane for both field sizes. Most results of the comparison of in-plane dose profiles derived from film measurements with those generated by the TPS were within the ±0.3 cm limits (see Figure 4a). However, for two centers, RA3 and RC5, these differences were greater for the 20% and 80% isodose levels with the results at the borderline of ±0.3 cm. For the cross-plane profiles, where the side of the field was shaped by the MLC leaves, the spread of the results was greater (see Figure 4b). Although the results for 50% isodose level were all within ±0.3 cm, six of 14 beams exceeded this limit for 20% or 80% isodose levels. One TPS beam profile differed from film profiles for both 80% and 20% dose levels. Most TPS cross-plane profiles that were inaccurately modeled for $2 \times 2\,cm^2$ fields were also showing differences to the film measurements for $2 \times 5\,cm^2$ fields. The highest differences exceeding ±0.5 cm were observed

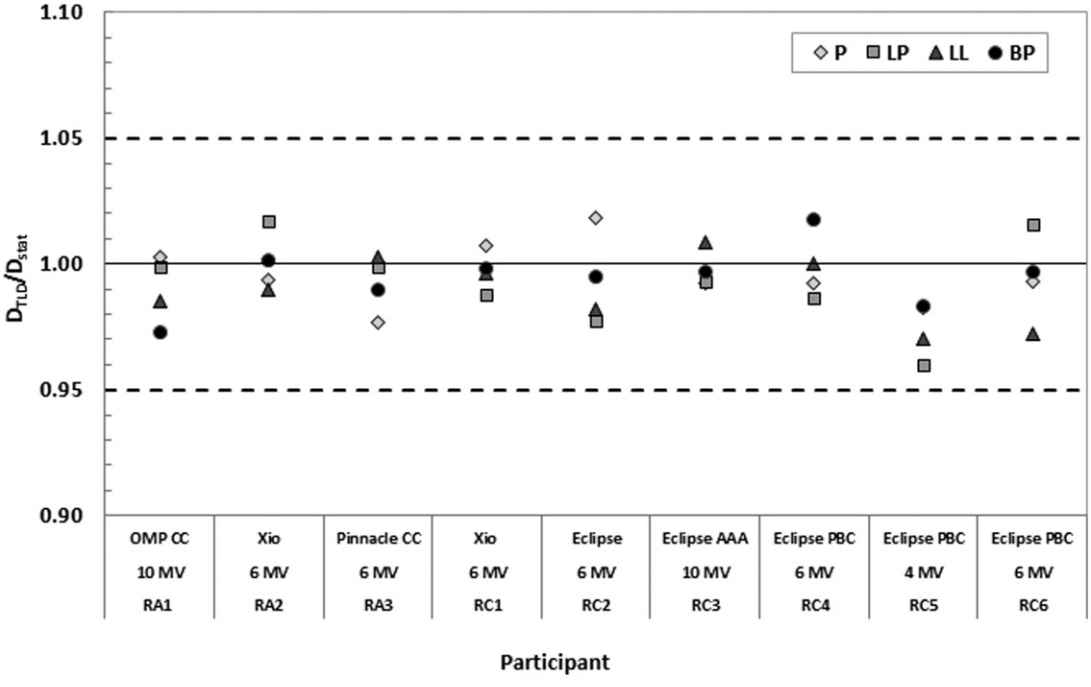
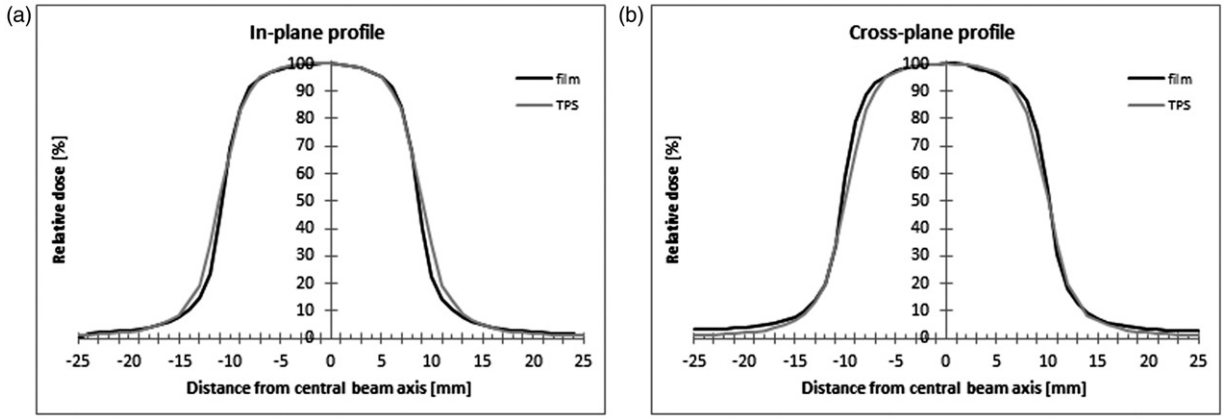
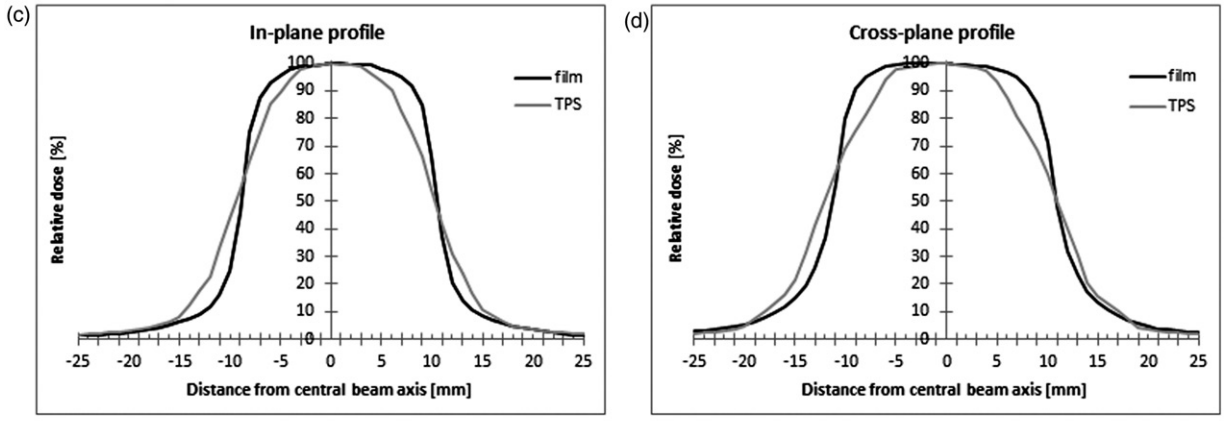


Figure 2. Ratio of D_{TLD}/D_{stat} for the four measurement points: P-polystyrene, LP-polystyrene with lung insert, LL-inside lung material and BP-polystyrene with bone insert. The dashed lines show the acceptance limits of ±5%.



Rel. Dose	TPS field size [mm]	Film field size [mm]	Film-TPS [mm]
80%	16.4	16.5	0.1
50%	**20.1**	**19.4**	**-0.7**
20%	23.9	22.7	-1.2

Rel. Dose	TPS field size [mm]	Film field size [mm]	Film-TPS [mm]
80%	16.4	17.4	1.1
50%	**20.1**	**20.5**	**0.4**
20%	24.0	23.8	-0.1



Rel. Dose	TPS field size [mm]	Film field size [mm]	Film-TPS [mm]
80%	13.8	14.9	1.1
50%	**19.7**	**19.2**	**-0.5**
20%	26.1	22.6	-3.5

Rel. Dose	TPS field size [mm]	Film field size [mm]	Film-TPS [mm]
80%	15.4	19.3	3.9
50%	**23.1**	**22.3**	**-0.9**
20%	29.4	27.5	-1.9

Figure 3. Comparison of in-plane and cross-plane profiles for a field size of 2×2 cm^2 showing good agreement (a) and (b) for participant RC2 and inadequate modeling by the TPS (c) and (d) for participant RA1 between profiles from film and TPS. Numerical values below the graphs give differences between the profiles widths at 80%, 50% and 20% isodose levels.

for the centers RA1 (OMP, 10 MV), RA3 (Pinnacle, 18 MV) and RC5 (Eclipse PBC, 4 MV). The follow-up on the discrepancies between the film and TPS profiles reflected upon the existing issues with TPS commissioning for small fields. The results of this study demonstrate that establishing the acceptance limits at ±0.3 cm level for 80%, 50% and 20% isodose levels for the national audit of small beam profiles relevant for IMRT may be challenging, although these limits are consistent with a commonly used distance-to-agreement value for QA of TPS plans [16].

As mentioned earlier, the doses calculated by TPS and delivered to films were independently checked with TLDs for the 2×5 cm^2 field size. The ratio of the TLD measured doses against the TPS calculated doses (D_{TLD}/D_{TPS}) were all within 5% acceptance limits, with the majority of results (11/14) within 3%.

Discussion

The dosimetry audit methodologies developed in consecutive CRPs and their results described here as well as in earlier publications [4–6] have demonstrated that dosimetry auditing expertise can successfully be developed and implemented in a step-by-step approach involving several national audit groups. When implementing more advanced radiotherapy techniques it is important to ensure that dose distributions relevant to more complex beam configurations are modeled correctly by the TPS. Simpler dose audits limited to reference and non-reference conditions are no longer sufficient. The audit Steps 5 and 6 described in this publication go beyond the so far existing audit steps.

It is not a straightforward task to assess the results of an audit for TPS calculations in the presence of heterogeneities as there are limitations of various calculation algorithms which are well known and described in the literature [17–19]. Jones and Das [20] presented the comparison between Monte Carlo and several clinically used algorithm calculations performed in the phantom with a lung insert. The analysis suggested that discrepancies in percentage depth dose curves are greater for higher energies, lower densities of heterogeneities and smaller fields. The differences observed were as high as 14% for the equivalent path length algorithm whereas, for Batho and convolution were, respectively, 8% and 4%. Gershkevitsh et al.

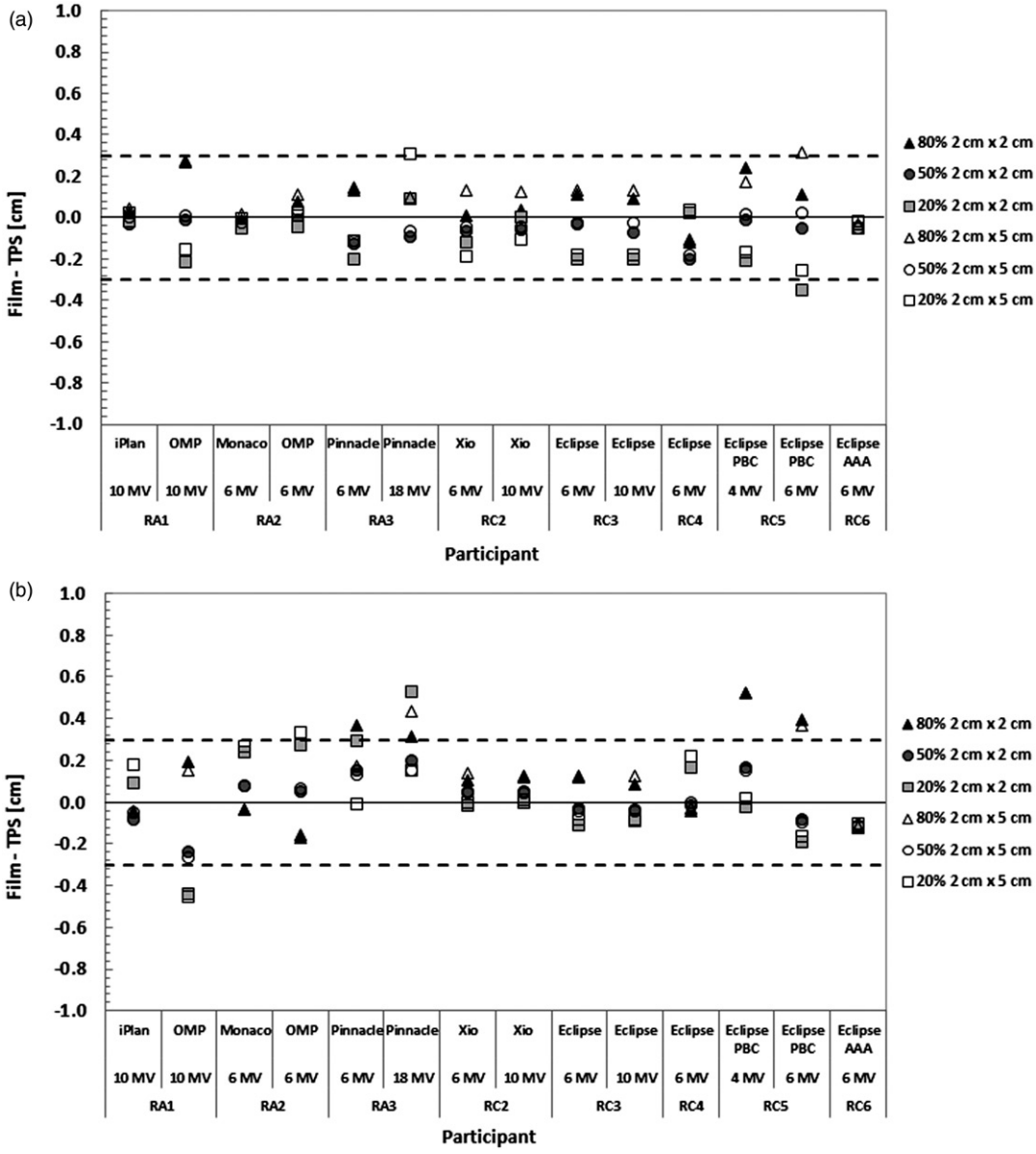


Figure 4. Differences between profiles from film and TPS at 80%, 50% and 20% isodose levels for the in-plane (a) and cross-plane (b) profiles for the 2×2 cm^2 and 2×5 cm^2 field sizes. The dashed lines indicate the level of ±0.3 cm.

in his study [19] showed that denser materials (bone equivalent) have smaller impact on calculations and differences they observed were around 3%. This finding is in line with the results of our study of the audit Step 5, showing no particular dosimetric issues for the phantom configuration involving the bone equivalent slab. Also, as mentioned earlier, algorithms' limitations need to be taken into account when comparing results from different audit participants. Step 5 auditing methodology described here is sensitive enough to detect deviations the TPS dose distributions, however, finding the reasons for deviations belongs to the follow-up process of poor audit results. The deviations other than resulting from the algorithm limitations may be attributed to incorrectly measured TPS input data, inaccuracies in the beam modeling or inaccurate CT to relative electron density conversion curves, and also erroneous beam calibrations.

It is well known [10] that the modeling of small fields in TPS needs careful attention as there are many factors that could lead to an error if not taken into account (lack of charged particle equilibrium, effects of source occlusion, dosimetry data used and detector specific issues). Several studies showed that it is not sufficient to just check central beam axis dose for small fields as the whole profile information is essential and differences in the penumbra region can affect patient treatments [21–23]. This is especially true in complex plans where fields consist of several small segments and the risks of delivering incorrect doses are high for OARs which normally lie close to high dose gradient regions. Good agreement for 50% isodoses between the measured and TPS generated dose distributions alone, does not mean that the rest of the profile is in agreement, as shown in Figure 3(c) and (d). The agreement of the MLC-shaped cross-plane profiles was less satisfactory than for the in-plane profiles; the reasons for that might be the leaf ends modeling by the TPS, inaccuracies in the TPS commissioning for small fields or positioning uncertainty of the MLC. The study carried out by Mu et al. [23] showed that systematic changes in leaf positioning of 1 mm can lead to

about 3% differences in the dose for simple IMRT plans, and about 10% for complex plans.

All centers taking part in this exercise had their TPS system commissioned for IMRT treatments; however, the information about the detectors used for the data collection for the beam configuration was not requested within the datasheet developed for this audit. The choice of detectors used for TPS commissioning have a big impact on beam modeling. Therefore follow-up procedures for poor audit results should verify more closely the TPS commissioning data including the type of detectors used for measurements. Yan et al. [21] showed that beam configurations based on the measurements with different detectors change the TPS calculation significantly; the passing rates of gamma evaluation for fields tested by that group changed by 11% when using different ionization chamber data. Similar results were reported by others [22] who noted that penumbra widening caused by the detector volume resulted in local dose differences of between 10% and 20% in the high dose gradient regions for IMRT fields. Azangwe et al. [24] produced a set of detector correction factors in small fields for a wide range of passive and active detectors, which are relevant for the commissioning of small fields.

As gafchromic films have high two-dimensional spatial resolution, they are appropriate detectors to use when checking dose profiles for small fields. Looking at the profiles in Figure 3 it can be seen that the difference in the dose is up to 20% in the penumbra region. This will not have a big impact on beam arrangements for the treatment where single field is used and only small part of volume surrounding PTV is overdosed, although the situation is different for IMRT where the composite field is built from several segments.

Participation in multi-center studies by national audit groups constitutes an important stage of testing the newly developed methodology prior to introducing new audits for more complex technologies and treatments at national levels. Within this CRP two multi-center studies were carried out to validate the audit methodology. The results indicate that the design of auditing procedures was adequate and the checks included in the audit program are able to detect various issues related to TPS beam modeling for the dose delivery exercises involved in the audit Steps 5 and 6. The phantom designed for these audit steps was found to be small enough to be used in postal audits and it was a generally a useful tool for auditing how TPS algorithms compute doses in the presence of heterogeneities. It was also demonstrated that checking profiles of small fields used for complex treatments, such as IMRT can be done using this phantom.

The development of the audit methodology continues with a subsequent IAEA CRP, which was initiated in 2014 and includes audits for small field output factors, MLC performance characteristics and 'end-to-end' remote audits of IMRT dose delivery. This new CRP is not addressed in this publication but largely follows the experience gained from the current and other existing postal dose audit programs [4,7,25].

To conclude, the IAEA encourages and supports the development of national audit programs for radiotherapy dosimetry with the scope of audits corresponding to the evolving complexity of radiotherapy. Implementation of such audit programs has a potential to improve the consistency of dosimetry practices among participating centers and may potentially reduce the number of dose misadministrations to patients undergoing radiotherapy.

Acknowledgments

This work was supported by the IAEA Co-ordinated Research Project E2.40.16. Ashland Inc. (USA) provided the project participants with licenses of the FilmQA Pro software and delivered a workshop on radiochromic film dosimetry. In-kind contributions by Ashland Inc. (USA) are gratefully acknowledged.

References

1. International Agency of Research on Cancer. 2012 – [cited 2015 Oct 1]. Available from:http://globocan.iarc.fr
2. International Atomic Energy Agency, Directory of Radiotherapy Centres. 1995 – [cited 2015 Oct 1]. Available from: http://www-naweb.iaea.org/nahu/dirac/
3. Izewska J, Dutreix A, Arib M, Saravi M, Castellanos E, Kaibao L, et al. Guidelines for the preparation of a quality manual for external audit groups on dosimetry in radiotherapy. IAEA/WHO Network of Secondary Standard Dosimetry Laboratories (SSDL) Newsletter; Vienna, 2002; 46 6–16.
4. Izewska J, Georg D, Bera P, Thwaites D, Arib M, Saravi M, et al. A methodology for TLD postal dosimetry audit of high-energy radiotherapy photon beams in non-reference conditions. Radiother Oncol 2007;84:67–74.
5. Izewska J, Bera P, Azangwe G. IAEA support to national TLD audit networks for radiotherapy dosimetry. In: Standards, applications and quality assurance in medical radiation dosimetry, (IDOS), Proceedings of an international symposium, Vienna, 9-12 November 2010. Vol 2. Vienna: IAEA; 2011. p. 443–51.
6. Ferreira IH, Dutreix A, Bridier A, Svensson H. ESTRO European assurance programme for radiation treatments (The EQUAL Network). In: Standards and Codes of Practice in Medical radiation Dosimetry, Proceedings of an international symposium, Vienna, 25-28 November 2002. Vol 2. Vienna: IAEA; 2003. p. 157–65.
7. Izewska J, Hultqvist M, Bera P. Analysis of uncertainties in the IAEA/WHO TLD postal dose audit system. Radiat Meas 2008;43:959–63.
8. Aspradakis MM, Byrne JP, Palmans H, Conway J, Roser K, Warrington J, et al. Small field MV photon dosimetry. Institute of Physics and Engineering in Medicine; York, 2010. Report No.: 103.
9. Fogliata A, Vanetti E, Albers D, Brink C, Clivio A, Knöös T, et al. On the dosimetric behaviour of photon dose calculation algorithms in the presence of simple geometric heterogeneities: comparison with Monte Carlo calculations. Phys Med Biol 2007;52:1363–85.
10. Das IJ, Ding GX, Ahnesjö A. Small fields: Nonequilibrium radiation dosimetry. Med Phys 2008;35:206–15.
11. Laub WU, Wong T. The volume effect of detectors in the dosimetry of small fields used in IMRT. Med Phys 2003;30:341–7.
12. Ong CL, Cuijpers JP, Senan S, Slotman BJ, Verbakel WFAR. Impact of the calculation resolution of AAA for small fields and RapidArc treatment plans. Med Phys 2011;38:4471–9.
13. Kron T, Clivio A, Vanetti E, Nicolini G, Cramb J, Lonski P, et al. Small field segments surrounded by large areas only shielded by a multileaf collimator: Comparison of experiments and dose calculation. Med Phys 2012;39:7480–9.
14. IAEA Technical Report Series 398. Absorbed dose determination in external beam radiotherapy. An international code of practice for dosimetry based on standards of absorbed dose to water. Vienna: IAEA; 2000.
15. Richter C, Pawelke J, Karsch L, Woithe J. Energy dependence of EBT-1 radiochromic film response for photon (10 kvp-15 MVp) and electron beams (6-18 MeV) readout by a flatbed scanner. Med Phys 2009;36:5506–14.
16. Ezzell GA, Burmeister JW, Dogan N, LoSasso TJ, Mechalakos JG, Mihailidis D, et al. IMRT commissioning: Multiple institution planning and dosimetry comparisons, a report from AAPM Task Group 119. Med Phys 2009;36:5359–73.

17. Kry S, Alvarez P, Molineu A, Amador C, Galvin J, Followill DS. Algorithms used in heterogeneous dose calculations show systematic differences as measured with the Radiological Physics Center's anthropomorphic thorax phantom used for RTOG credentialing. Int J Radiat Oncol Biol Phys 2012;85:95–100.
18. Krieger T, Sauer A. Monte Carlo- versus pencil-beam-/collapsed-cone-dose calculation in a heterogeneous multi-layer phantom. Phys Med Biol 2005;50:859–68.
19. Gershkevitsh E, Pesznyak C, Petrovic B, Grezdo J, Chelminski K, Lopes MC, et al. Dosimetric inter-institutional comparison in European radiotherapy centres: Results of IAEA supported treatment planning system audit. Acta Oncol 2014;53:628–36.
20. Jones AO, Das IJ. Comparison of inhomogeneity correction algorithms in small photon fields. Med Phys 2005;32:766–76.
21. Yan G, Fox C, Liu C, Li JG. The extraction of true profiles for TPS commissioning and its impact on IMRT patient specific QA. Med Phys 2008;35:3661–70.
22. Van Esch A, Bohsung J, Sorvari P, Tenhunen M, Paiusco M, Iori M, et al. Acceptance tests and quality control (QC) procedures for the clinical implementation of intensity modulated radiotherapy (IMRT) using inverse planning and the sliding window technique: experience from five radiotherapy departments. Radiother Oncol 2002;65:53–70.
23. Mu G, Ludlum E, Xia P. Impact of MLC leaf position errors on simple and complex IMRT plans for head and neck cancer. Phys Med Biol 2007;53:77–88.
24. Azangwe G, Grochowska P, Georg D, Izewska J, Hopfgartner J, Lechner W, et al. Detector to detector corrections: a comprehensive experimental study of detector specific correction factors for beam output measurements for small radiotherapy beams. Med Phys 2014;41:072103
25. Ibbott GS, Followill DS, Molineu HA, Lowenstein JR, Alvarez PE, Roll JE. Challenges in credentialing institutions and participants in advanced technology multi-institutional clinical trials. Int J Radiat Oncol Biol Phys 2008;71:71–5.