Jurnal Sains Kesihatan Malaysia 23 (1) 2025: 90-96
DOI : http://dx.doi.org/10.17576/JSKM-2025-2301-01

Treatment Planning System Dose Verification for MLC-Shaped Photon Beams in Postal Radiotherapy Dosimetry Audit: A Single-Centre Pilot Study

(Pengesahan Dos Sistem Perancangan Rawatan untuk Medan Foton Dibentuk MLC dalam Audit Dosimetri Radioterapi Secara Pos: Kajian Perintis Pusat Tunggal)

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Abstract

This study aimed to initiate the fourth consecutive phase of remote dosimetry auditing by the International Atomic Energy Agency (IAEA) for radiotherapy facility in Malaysia, which focuses on the validation of the treatment planning system (TPS) doses for photon beams shaped using multileaf collimators (MLC). Thermoluminescence dosimeter (TLD-100), encased within plastic capsules, were dispatched to the radiotherapy centre along with an IAEA TLD holder, irradiation datasheets, and technical instructional booklet. The irradiation setup involved exposing the TLD-100 to assess dose variations concerning field size and configuration across a range of MLC-shaped segments, encompassing both regular and irregular geometries, including wedged fields. Each capsule received an irradiation dose of 2 Gy using 6- and 10 MV photon beams. A comparison was made between the dose calculated by the TPS (D_{TPS}) and the doses measured by both the ionization chamber (D_{IC}) and TLD-100 (D_{TLD}). No deviations exceeding ±5% of all measurements over D_{TPS} were observed. The mean ratios were 1.007 ± 0.014 and 1.003 ± 0.004 for D_{IC}/D_{TPS} with 6- and 10 MV beams, respectively, while D_{TLD}/D_{TPS} recorded mean ratios of 1.023 ± 0.007 for 6 MV and 1.009 ± 0.022 for 10 MV beams. This project marks the successful initiation of dose verification for the TPS in accordance with IAEA guidelines, enabling the assessment of dosimetric data related to the use of MLC. A recommendation was put forth to expand the scope of the postal dosimetry audit at the national level, with the goal of improving radiotherapy treatment dose precision.

Keywords: Treatment planning system; dose verification; dosimetry audit; multileaf collimator

Abstrak

Kajian ini bertujuan untuk memulakan fasa keempat berurutan pengauditan dosimetri jarak jauh oleh Agensi Tenaga Atom Antarabangsa (IAEA) untuk fasiliti radioterapi di Malaysia, yang memfokuskan pada pengesahan dos sistem perancangan rawatan (TPS) untuk medan foton yang dibentuk menggunakan kolimator berbilang bilah (MLC). Dosimeter pendarcahaya terma (TLD-100), yang diletakkan dalam kapsul plastik, telah dihantar ke pusat radioterapi bersama pemegang TLD IAEA, lembaran data penyinaran dan buku panduan teknikal. Persediaan penyinaran melibatkan pendedahan TLD-100 untuk menilai variasi dos berkenaan saiz medan dan konfigurasi merentas julat segmen yang dibentuk MLC, merangkumi kedua-dua geometri biasa dan tidak sekata, termasuk medan berbaji. Setiap kapsul menerima dos penyinaran sebanyak 2 Gy menggunakan medan foton 6- dan 10 MV. Perbandingan dibuat antara dos yang dikira oleh TPS (D_{TPS}) dan dos yang diukur oleh kedua-dua kebuk pengionan (D_{IC}) dan TLD-100 (D_{TLD}). Tiada sisihan melebihi ±5% daripada semua pengukuran ke atas D_{TPS} diperhatikan. Nisbah min ialah 1.007 ± 0.014 dan 1.003 ± 0.004 untuk D_{IC}/D_{TPS} bagi medan 6- dan 10 MV, manakala D_{TLD}/D_{TPS} merekodkan nisbah min 1.023 ± 0.007 untuk 6 MV dan 1.009 ± 0.022 untuk 10 MV. Projek ini menandakan kejayaan bagi permulaan pengesahan dos untuk TPS mengikut garis panduan IAEA, membolehkan penilaian data dosimetrik yang berkaitan dengan penggunaan MLC. Cadangan telah dikemukakan untuk meluaskan skop audit dosimetry secara pos di peringkat kebangsaan, dengan matlamat untuk meningkatkan ketepatan dos rawatan radioterapi.

Kata kunci: Sistem perancangan rawatan; pengesahan dos; audit dosimetri; kolimator berbilang bilah

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INTRODUCTION

A multileaf collimator (MLC) is an essential component in modern linear accelerator external beam radiation therapy systems, designed to shape the radiation beam precisely to match the contours of the tumour or treatment area. The leaves of the MLC can be meticulously arranged to define the shape of the radiation beam with precision. This capability enables the delivery of radiation to the target area with heightened accuracy, thereby reducing adverse effects and enhancing the overall effectiveness of the treatment (Hosseinzadeh et al. 2017; Acun et al. 2015). Each leaf's independent mobility, together with the inverse planning process, allows for the formation of intricate and irregular geometries, permitting the use of more advanced treatments like as intensity-modulated radiation therapy (IMRT) and volumetric-modulated arc therapy (VMAT) (O'Daniel et al. 2023; Wesolowska et al. 2019). These techniques make it possible to administer radiation doses that conform closely and precisely to the tumour while safeguarding adjacent healthy tissues. The computer system governs the movement of each individual leaf, relying on data from the treatment planning software to ensure accurate radiation delivery (Lechner et al. 2018).

A comprehensive plan for delivering radiation therapy to a patient is devised using specialized software known as a treatment planning system (TPS). One of its primary functions is to compute the dosage based on the treatment plan and the physical properties of the radiation beams. Following the loading of image datasets and tumour identification, the systems proceed to develop a detailed plan for the path of each treatment beam, outlining how the therapy system will deliver radiation to the patient. Additionally, TPS calculates the anticipated dose distribution within the patient's tissue, accounting for factors like the energy level penetration through different tissue types encountered by the beamlines (Wang et al. 2020). Advancements in technology have led to the continual evolution of TPS, with the integration of artificial intelligence and machine learning techniques aimed at enhancing automation and precision in treatment planning (Chamunyonga et al. 2020). These systems are indispensable in modern radiation therapy, providing valuable support to radiation oncologists and medical physicists as they develop customized treatment strategies for individual patients.

Dosimetry quality assurance (QA) for TPS is designed to identify errors or inconsistencies in the treatment planning algorithm before they can impact patient care. This proactive approach enables the resolution of issues before they become critical. The International Atomic Energy Agency (IAEA), an external independent organization, has developed a specific dosimetry protocol to enhance QA in treatment delivery (Izewska et al 2016; Gershkevitsh et al. 2014). The IAEA has established a total of nine comprehensive sequential postal dosimetry audit protocols to ensure complete dosimetry QA in radiotherapy treatment delivery (IAEA 2023). The significance of quality audits in radiotherapy, and their impact on dosimetry and clinical procedures, has received widespread recognition (Clark et al. 2018; Kry et al. 2018; Pasler et al. 2018). These audits provide an impartial assessment of reference dosimetry in radiotherapy centres worldwide by validating the actual output of radiotherapy machines.

It becomes critical to assess various aspects of the delivery process through auditing systems as radiation treatment techniques progress toward dynamic methods (Geurts et al. 2022; Akino et al. 2018). This ensures a reasonable level of confidence that a radiotherapy facility is adhering to best practices when administering specific treatments. Validating the complex radiation treatment techniques involving the delivery of non-uniform intensity beams through the MLC is becoming increasingly important since IMRT becoming a standard clinical practice in all Malaysian radiotherapy centres. However, the widespread use of MLC surpasses the current capabilities of the dosimetry audit program in Malaysia, which is currently limited to IAEA level III dosimetry audit protocols (Fadzil et al. 2022a; Abdullah et al. 2022). Consequently, there is a rising demand for dosimetry audits, especially at more advanced audit levels concerning photon beams shaped with irregular MLCs. The present study was conducted to initiate a level IV dosimetry audit for photon beams shaped with MLC fields, aiming to support the ongoing IAEA QA program on the independent experimental verification of the dose calculated by TPS.

MATERIALS AND METHODS

Audit workflow

The postal dosimetry audit involved a six-step process, as detailed in Figure 1. Initially, the TLD-100 in powder form underwent annealing, following the manufacturer's recommended thermal treatment profile (Thermo 2002), utilizing a programmable furnace (PTW Freiburg, Germany). The TLD-100, comprising 155 ± 10 mg, was then enclosed within a plastic capsule, forming part of the dosimetry package. Subsequently, the measuring centre dispatched the dosimetry package to the audited radiotherapy centre. This package included the IAEA standard holder, a TLD separator box, an instruction booklet, and data sheets. Each separator box was appropriately labeled with "TLD 1 to 7", corresponding to seven distinct MLC-shaped beams to be irradiated.

DOI : http://dx.doi.org/10.17576/JSKM-2025-2301-01

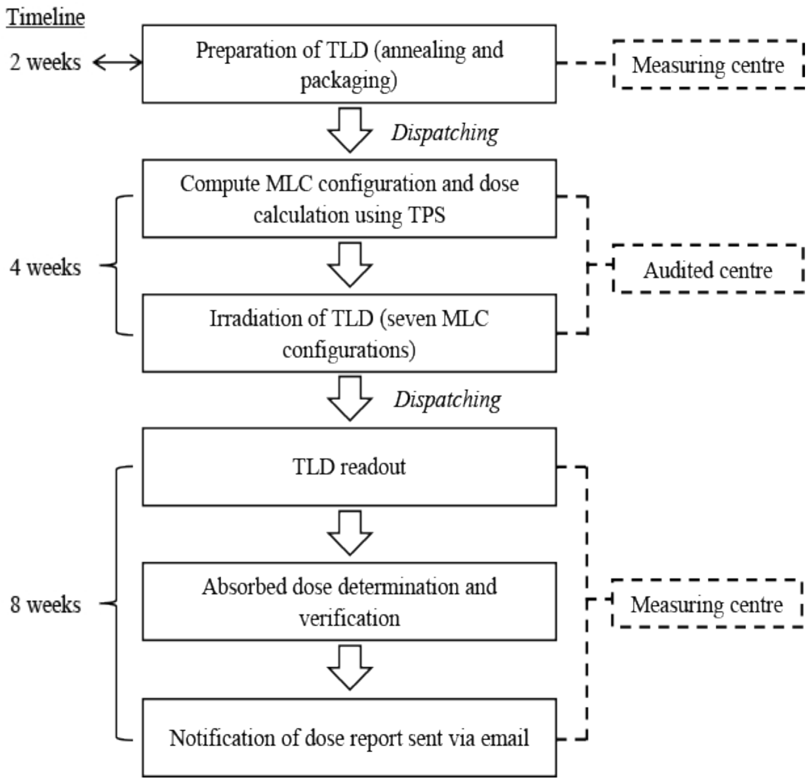

Figure 1 The workflow diagram provides a graphic overview of the postal audit process.

TLD irradiations

Two batches of TLDs were dispatched to the audited facility, where a single institutional irradiation of irregular MLC fields was carried out at two specified energy levels: 6- and 10 MV. The irradiation setups were planned by the physicist using the in-house TPS to ascertain the appropriate monitor units (MUs) required for delivering a prescribed dose of 2 Gy to the on-axis TLDs. This calculation was based on standard irradiation parameters, including a 100 cm source-to-surface distance (SSD) and a 10 cm depth in water. Figure 2 shows the MLC collimation settings for seven irregular shapes that replicate complex treatment techniques, including square, small, inverted Y, circular, and rectangular fields. This audit of irregular fields was the fourth consecutive remote dosimetry audit within a series of nine sequential audit programs established by the IAEA. These audit methodologies were developed based on a series of coordinated research projects worldwide and primarily utilize thermoluminescent dosimetry (IAEA 2023). The irradiation parameters are summarized in Table 1. To experimentally determine the absorbed dose to water in the MLC-shaped beams for the reference measurement, the absorbed dose measurement was carried out using an ionization chamber, in accordance with the established dosimetry protocol, and the data sheet was subsequently completed.

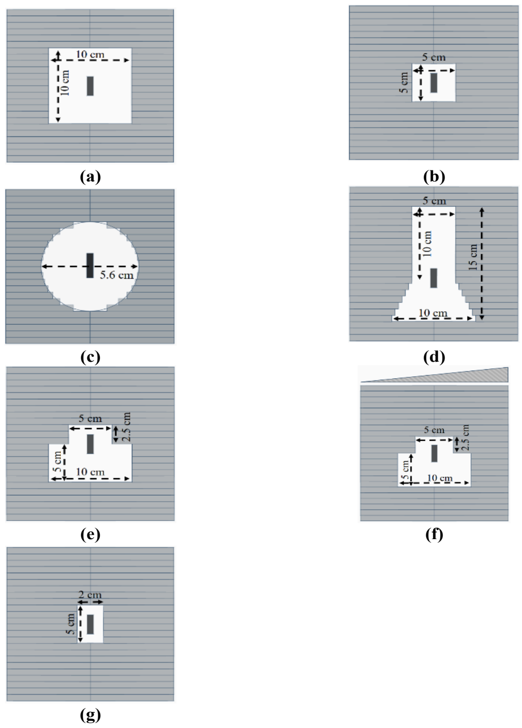

Figure 2 Schematic illustration of the MLC-shaped irradiation beams for (a) reference output, (b) small field, (c) circular, (d) inverted Y, (e) irregular, (f) irregular wedged, and (g) small rectangular fields based on the beam view. The selection of leaf positions should aim to closely mimic the setup procedures that would be necessary when treating a patient with these specific field configurations.

Table 1 Irradiation parameters for irregular MLC-shaped audit.

Field label	Field name	Field size	Delivered dose
TLD 1	Reference output	10 cm × 10 cm	2 Gy
TLD 2	Small square	5 cm × 5 cm with MLC	2 Gy
TLD 3	Circular	5.6 cm diameter with MLC	2 Gy
TLD 4	Inverted Y	15 cm × 10 cm with MLC	2 Gy
TLD 5	Irregular	10 cm × 7.5 cm with MLC	2 Gy
TLD 6	Irregular wedged	10 cm × 7.5 cm with MLC	2 Gy
TLD 7	Small rectangular	2 cm × 5 cm with MLC	2 Gy

Dose measurements and notification

A powder dispenser was employed to position the TLD-100 on the planchet, ensuring consistent delivery of ~15 mg of the powder. Subsequently, a thermal treatment was applied, following the described heating cycle (Al-Haj et al. 2007), with the TL output measured in units of electrical charge. This entire procedure was executed carefully to prevent any powder loss during dispensing, thereby minimizing variations in the readings. The relationship between the TL output and the absorbed dose (D_{TLD}) can be expressed as:

$$D_{TLD} = R_{TLD} \times N_{TLD} \times K_{hol} \times K_{fad}$$

Equation 1

where R_{TLD} and N_{TLD} are the mean of the ten TLD-100 readings from each capsule and the calibration coefficient of the TLD-100, respectively. K_{hol} represents the correction factor for the TLD holder, while K_{fad} is the correction factor for TLD-100 powder signal fading post-irradiation. The percentage relative deviation between the stated dose by the TPS (D_{sta}) and the measured dose by the TLD-100 (D_{mea}) was then calculated. The deviation between stated and measured doses is given by the expression:

$$\Delta D = [D_{sta} - D_{mea}]/D_{mea} \times 100$$

Equation 2

The deviation has been set into three categories:

(1) Acceptance level: deviation is less than ± 5%.
(2) Action level (minor): deviation is between ± 5% and 10%.
(3) Emergency level (major): deviation is greater than ± 10%.

Comprehensive information regarding the audit dose report is sent via email to the audited centre in the event that the deviation falls within the established acceptance limit. However, if a deviation exceeding the tolerance threshold (whether major or minor) is detected, the participating centre is notified of the occurrence of a deviation. They are then requested to promptly reperform the measurement. If, after the repeat measurement, a subsequent deviation of greater than ±5% is observed, it may necessitate a thorough on-site audit visit conducted by the measuring centre (Izewska et al. 2020; Santos et al. 2019).

RESULTS

The ongoing TLD postal dosimetry audit, which focuses on high-energy radiotherapy photon beams shaped using an MLC and utilizes TLD-100, represents a pioneering initiative within Malaysian radiotherapy facilities. This audit is conducted using a Varian True Beam linear accelerator, which was initially installed in 2016. The calibration of megavoltage beams from the linear accelerator is accomplished with a Wellhofer Farmer Type Chamber (FC23-C) ionization chamber, with a calibration traceable to the Secondary Standard Dosimetry Laboratory (SSDL) of the Malaysia Nuclear Agency. The adoption of the TRS-398 (IAEA 2000) dosimetry protocol by this audited centre during calibration signifies a reduction in the uncertainty associated with radiotherapy beam dosimetry and establishes a standardized and cohesive framework.

Figure 3 illustrates the percent deviation from the stated dose by TPS for all 14 MLC fields audited, encompassing both 6- and 10 MV beams. The results consistently fell within a range of less than ±5%, aligning with the acceptance limit recommended by the IAEA. The highest observed percentage deviation was 4.12%, while the lowest was a mere 0.02%, both of which were recorded for 10 MV photon beams. Among these measurements, two exhibited a positive relative deviation, indicating that the audited centre stated a higher dose than that measured by the TLD-100, while the rest contributed to a negative relative deviation, signifying the opposite scenario. Since this centre had previously taken part in the postal dosimetry audit under reference conditions (level I), the results of the current audit demonstrate consistency in calibration output.

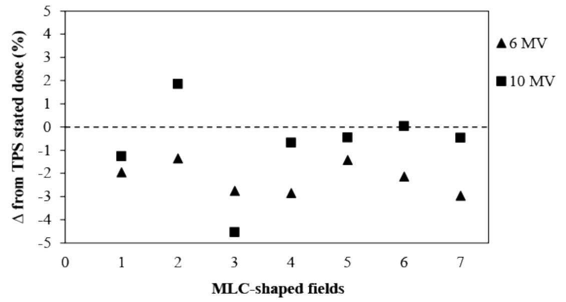

Figure 3 Distribution of percentage relative deviation from TPS stated dose of 14 measurement points.

The measurement of the absorbed dose using an ionization chamber (D_{IC}) was conducted alongside TLD (D_{TLD}) measurements to validate the calculated dose delivered to water by the TPS at a dose of 2 Gy. For 6 MV measurements, the mean D_{IC}/D_{TPS} ratio was 1.007 ± 0.014, and for 10 MV, it was 1.003 ± 0.004. As for D_{TLD}/D_{TPS}, the ratio ranged from 0.982 to 1.053 for both 6- (Figure 4) and 10 MV (Figure 5) photon beams. Additionally, when comparing the output factor to the TPS calculated values using TLD-100 (D_{TLD}/D_{TPS}), the mean ratio was 1.023 ± 0.007 for 6 MV and 1.009 ± 0.022 for 10 MV. Of interest is that when comparing the mean ratio of TLD-100 measurements directly to the mean ratio of absorbed dose measured by the ionization chamber to the TPS, it was found that the TLD-100 exhibited a higher deviation of 2.26% and 0.91% for 6- and 10 MV, respectively.

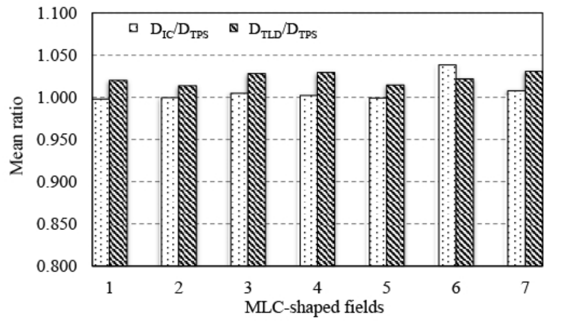

Figure 4 The ratio of doses measured by the ionization chamber and TLD-100 relative to the dose calculated by the TPS for 6 MV photon energy.

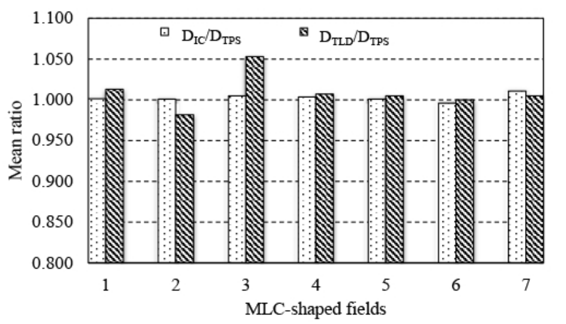

Figure 5 The ratio of doses measured by the ionization chamber and TLD-100 relative to the dose calculated by the TPS for 10 MV photon energy.

DISCUSSION

The majority (86%) of the audited MLC fields exhibit a negative percentage deviation, which is interesting to notice because it means that the TLD-100 recorded a larger dose than what the TPS initially had calculated. Several factors come into play when determining the absorbed dose in water using TLD-100, with dosimeter uniformity and consistency being among them. TLD-100 powder is employed as a remote dosimeter for independent dose audits due to its cost-effectiveness in distributing a high-volume dosimeter nationwide or globally, which is facilitated by its straightforward logistical management. However, TLD-100 powder exhibits discrepancies stemming from the irregular distribution of the powder above the heated planchet, which happens at varying times during the readout, highlighting its reliance on the operator in this process. In comparison to palletized dosimeters, powder-based TLD-100 offers fewer benefits in terms of batch uniformity and excellent dimensional consistency (Alanazi et al. 2023).

This article emphasizes the reliability of the audited centre's performance. It was observed that during a previous involvement in the postal dosimetry audit under reference conditions (Abdullah et al. 2016), the measured discrepancies remained within the acceptance limit recommended by the IAEA. It was revealed that one of the crucial factors for maintaining beam output within tolerance levels is the familiarity of the medical physicist with the postal dosimetry audit program. This familiarity helps in preventing errors in dosimeter irradiation, such as selecting the incorrect energy, MLC field shape, or SSD (Kry et al. 2018; Kry et al. 2017). This centre, therefore, demonstrated a connection between the frequency of participation in the auditing program and their proficiency in conducting the audit. This underscores the importance of radiation facilities engaging in regular external audits to attain and sustain a sufficient level of dosimetry quality (Izewska et al. 2002).

To obtain absolute dose measurements, it is essential that the ionization chambers used are calibrated with reference to primary standards. The ionization chamber used in this audited centre undergoes regular periodic calibration at the SSDL, Malaysia Nuclear Agency, ensuring that all relevant parameters can be traced back to the International Bureau of Weights and Measures (BIPM). At a 95% confidence level, the SSDL maintains an uncertainty level of 1.22% (Fadzil et al. 2022b; Fadzil et al. 2022c). Utilizing an ionization chamber that is traceable to primary standards is a prerequisite before employing it in clinical dosimetry. This requirement, combined with an accurate experimental setup and the correct interpretation of the dosimetry protocol to determine and accurately apply the necessary factors for converting the dosimeter readings into absorbed doses in water at the calibration point, constitutes the three fundamental criteria for calibrating megavoltage beams from a linear accelerator.

CONCLUSION

This study, which is part of the fourth consecutive series of remote dosimetry audits by the IAEA, is the first of its kind to be carried out in Malaysia. This pilot audit covers a comprehensive examination of dose variation along the beam axis concerning field size and shape, encompassing a variety of MLC-shaped fields, including wedged fields. Additionally, the study successfully assesses the hospital's methodology for calculating these dosimetric parameters, which was carried out using the local TPS. All recorded percentage deviations from the stated dose remained within the recommended acceptance limit set by authorities, which is ±5%. This positive outcome has led to a recommendation to expand the scope of the postal dosimetry audit to a nationwide scale, aiming to enhance treatment accuracy across the entire country. On a larger scale, this initiative will evaluate and compare the performance of first-time participants with that of radiotherapy centres that have undergone the postal dosimetry program on multiple occasions.

ACKNOWLEDGEMENT

This research is supported in part by GGPM-2021-032 from Universiti Kebangsaan Malaysia. The authors also extend their appreciation to the Malaysian Nuclear Agency and Department of Radiology, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia for the use of their research facilities.

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