IAEA/WHO TLD POSTAL DOSE AUDIT SERVICE AND HIGH PRECISION MEASUREMENTS FOR RADIOTHERAPY LEVEL DOSIMETRY

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Abstract — Since 1969 the International Atomic Energy Agency (IAEA), together with the World Health Organization (WHO), has performed postal TLD audits to verify calibration of radiotherapy beams in developing countries. The TLD programme also monitors activities of Secondary Standard Dosimetry Laboratories (SSDLs). The programme has checked approximately 4000 clinical beams in over 1100 hospitals, and in many instances significant errors have been detected in the beam calibration. Subsequent follow-up actions help to resolve the discrepancies, thus preventing further mistreatment of patients. The audits for SSDLs check the implementation of the dosimetry protocol in order to assure proper dissemination of dosimetry standards to the end-users. The TLD audit results for SSDLs show good consistency in the basic dosimetry worldwide. New TLD procedures and equipment have recently been introduced by the IAEA that include a modified TLD calibration methodology and computerised tools for automation of dose calculation from TLD readings.

INTRODUCTION

In 1969 the International Atomic Energy Agency (IAEA), together with the World Health Organization (WHO), established the IAEA/WHO TLD postal programme to verify the calibration of radiotherapy beams in developing countries\(^{1,2}\). The main purpose of this programme is to provide an independent quality audit of the dose delivered by radiotherapy treatment machines using a thermoluminescence dosemeter (TLD) as transfer dosemeter. Since 1981 the TLD programme has also monitored activities of the Secondary Standard Dosimetry Laboratories (SSDLs) with the goal of achieving consistency in basic dosimetry throughout the world\(^3\).

The TLD audits are implemented through a close collaboration between the IAEA and WHO. The IAEA is responsible for the scientific and technical aspects of the programme, including the evaluation of the TLDs and resolving discrepancies detected, whereas WHO coordinates distribution of the TLDs to radiotherapy hospitals.

The TLD programme has been strengthened with new procedures and equipment that improve its overall efficiency. Due to the automation of the TLD system and the development of computerised tools for dose calculation from the readings, the IAEA has substantially increased its capacity and doubled the annual number of TLD audits.

The IAEA/WHO TLD programme is supported by the International Bureau of Weights and Measures (BIPM), Primary Standard Dosimetry Laboratories (PSDL), international and national TLD networks operating in Europe and North America and some advanced radiotherapy centres. These institutes exchange reference irradiations with the IAEA/WHO TLD programme, acting as a reciprocal external quality control of the experimental component of the programme.

The activities of the TLD programme, including recent developments in laboratory procedures and the results of audits for radiotherapy hospitals, and SSDLs are described here.

THE IAEA TLD SYSTEM FOR RADIOTHERAPY DOSIMETRY

The TL dosemeters used in the IAEA/WHO TLD programme are polyethylene capsules of 20 mm inner length, 3 mm inner diameter, filled with approximately 155 mg of TLD powder. The TL material currently used is a virgin lithium fluoride powder, LiF:Mg,Ti, type TLD-100 (Harshaw). The TLD powder is annealed before it is used for dose measurements in order to optimise the LiF characteristics. The annealing is performed at 400°C for 1 hour followed by fast cooling and subsequent annealing at 80°C for 24 h. Since the dosimetric characteristics of the LiF powder are closely related to its grain size and homogeneity, the powder is sifted after annealing to eliminate the smallest grains (below 80 \(\mu\)m). The good homogeneity of the powder allows the routine testing of only a small sample in order to determine radiation response characteristics representative for the whole manufacturer’s lot. Before its use, the powder is stored for at least 2 weeks after annealing to stabilise its sensitivity.

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Since 1998, a PCL3 TLD automatic reader (Fimel, France) has been routinely used in the IAEA for the measurements of TL dosimeters\(^9\). The PCL3 reader provides fast readings of a large number of TLD samples with a reproducibility of 0.4% (one standard deviation). Four readings per TL capsule are made.

Due to the automation of the TLD system and the development of computerised tools for dose calculation from the readings, the annual number of TLD audits was increased from 200–300 beam checks in the past to approximately 500 checks at present.

In order to determine the absorbed dose to water (\(D_w\)) from the reading of TL dosimeters, a calibration of the TLD system is performed and several correction factors and coefficients applied. These correct for non-linearity in dose response, beam quality and TLD holder attenuation at that quality\(^{5,6,7}\) and fading. The calibration characteristics are determined separately for each batch of powder. Samples taken from the same batch are considered to have the same fading, dose response, and energy dependence. In the IAEA/WHO TLD programme, the fading correction is not relevant because the system calibration is performed at the same time as the irradiation of the dosemeters by the users. For this purpose, the irradiation windows are established. The TLD response per unit of absorbed dose to water is determined by irradiating in a \(^{60}\)Co beam a set of TLDs to different doses under the standard configuration (field size \(10 \times 10 \text{ cm}^2\) at 1 m from the source, at a depth in water of \(5 \text{ g.cm}^{-2}\)). Before 2000, the absorbed dose to water at the position of the TLDs was determined from the readings of an ionisation chamber calibrated in terms of air kerma by BIPM and using the IAEA Code of Practice TRS-277\(^7\). From the beginning of 2000 the absorbed dose has been determined using an ionisation chamber calibration factor in terms of absorbed dose to water and the TRS-398\(^8\). The new ion chamber calibration is also traceable to BIPM.

The combined relative standard uncertainty \(u_c\) (coverage factor \(k = 1\))\(^9\) of the determination of the \(D_w\) from TLD measurements has two components: (i) the uncertainty of the calibration of the TLD system from the determination of the \(D_w\) using an ion chamber and (ii) the uncertainty in the TLD procedure itself. The latter includes the uncertainty of the process of reading the TLD (corrected for daily fluctuations of the reader) and the uncertainties of the individual coefficients and correction factors mentioned above. The relative standard uncertainty of the TLD procedure (ii) is estimated to be 1.7%. It is mainly dominated by the uncertainty in the TLD non-linearity dose response and beam quality corrections. The uncertainty in the calibration of the TLD system (i) arises mainly from the uncertainty of the determination of the absorbed dose in reference conditions from the ionisation chamber measurements, \(u(D_w)\), using the dosimetry codes of practice\(^{5,8}\). This increases the combined relative standard uncertainty of the entire TLD process \(u_c\) from 1.7% to 2.3%. It should be noticed, however, that when the same dosimetry protocol is used at a hospital or laboratory to determine the dose given to the TLD, most of its contribution in \(u(D_w)\) cancels out.

### QUALITY CONTROL OF THE IAEA/WHO TLD SYSTEM

The IAEA maintains a strict internal quality control of the TLD system. The system calibration is verified at every reading session and the dose response and fading are verified at the commissioning of every new lot of powder. These are followed by an internal verification (self-test) of the reproducibility in dose determination with the TLDs. The irradiation of TLDs for deriving the energy response at high-energy photon beams is made by one of the reference radiotherapy centres for every batch of powder mailed to the users.

An example of the distribution of the relative TL response corrected for the reader’s fluctuations for 345 TLD sets irradiated at the IAEA laboratory with absorbed dose to water of 2 Gy in standard conditions (field size \(10 \times 10 \text{ cm}^2\) at 1 m from the source, at a depth in water of \(5 \text{ g.cm}^{-2}\)) is shown in Figure 1. The mean of the distribution is 1.000 and the standard deviation is 0.8%. Each data point represents the average of 2 TL dosemeters (8 TL readings).

External verifications of the accuracy of the dose determination by the IAEA/WHO TLD system are also performed systematically, for every TLD batch mailed to radiotherapy hospitals or laboratories, through reference irradiations by the BIPM, two PSDLs (the Bundesamt für Eich- und Vermessungswesen (BEV) in Austria, and the Physikalisch-Technische Bundesanstalt (PTB) in Germany), three international TLD networks

![Figure 1. Distribution of the relative TL response corrected for the reader’s fluctuations for 345 TLD sets irradiated at the IAEA laboratory to 2 Gy of the absorbed dose to water in standard conditions (field size \(10 \times 10 \text{ cm}^2\) at 1 m from the \(^{60}\)Co source). The mean of the distribution is 1.000 and the standard deviation is 0.8%. Each data point represents the average of 2 TL dosemeters (8 TL readings).](image-url)
operating in Europe and the USA, EQUAL (ESTRO Community Quality Assurance network), EC QA network (European Community Quality Assurance network within the programme ‘Europe against Cancer’), and the Radiation Physics Centre (RPC) in Houston, USA, and four university hospitals with a recognised prestige in dosimetry. The results of the reference irradiations provided during 1998–2000 by the BIPM and two PSDLs are shown in Figure 2. The graph shows ratios of the IAEA’s determined absorbed dose to those stated by the BIPM or the PSDLs, \(D_{\text{IAEA}}/D_{\text{PSDL}}\). Each data point corresponds to the average of three dosemeters and results of 43 reference irradiations with \(^{60}\text{Co}\) beams are shown. The mean of the distribution is 1.000 and the standard deviation is 0.7%. The mean ratios for the individual laboratories are: 1.000 for BIPM, 0.999 for BEV and 1.003 for PTB. The results vary between a minimum ratio of 0.986 and a maximum of 1.014. The results of the reference irradiations provided during 1998–2000 by the TLD networks and reference hospitals are shown in Figure 3. The graph shows ratios of the IAEA-determined absorbed dose to that stated by the reference institution, \(D_{\text{TLD}}/D_{\text{stat}}\). Each data point corresponds to the average of three dosemeters and results of 101 reference irradiations are shown including 26 \(^{60}\text{Co}\) and 75 high-energy X ray beams. The mean of the distribution is 1.000 and the standard deviation is 1.1%. The results vary between a minimum ratio of 0.968 and a maximum of 1.023. The change of the IAEA beam calibration in the beginning of 2000 from air kerma to the new energy X ray beams. The mean of the distribution is 1.000 and the standard deviation is 0.7%. The mean ratios of the IAEA-determined dose (\(D_{\text{TLD}}\)) relative to the dose stated by the institution (\(D_{\text{stat}}\)) each data point corresponds to the average of three dosemeters and results of 101 reference irradiations are shown which include 26 \(^{60}\text{Co}\) and another for high-energy X rays. Results of this programme indicate that typically more than 95% of the SSDLs which participate in the annual TLD audits have results within the \(\pm 3.5\%\) acceptance limits. For laboratories with deviations outside the acceptance limits, a follow-up programme has been established to resolve the discrepancies. Those laboratories are informed by the IAEA about the discrepancy and assisted to understand and resolve the discrepancies.

The IAEA/WHO TLD postal dose quality audit service has monitored the performance of the SSDLs in the therapy dose range since 1981. The audits are organised annually in two irradiation runs, which total approximately 80 beam checks per year. The SSDLs active in radiotherapy level dosimetry are offered two beam checks, one for \(^{60}\text{Co}\) and another for high-energy X rays. Results of this programme indicate that typically more than 95% of the SSDLs which participate in the annual TLD audits have results within the \(\pm 3.5\%\) acceptance limits. For laboratories with deviations outside the acceptance limits, a follow-up programme has been established to resolve the discrepancies. Those laboratories are informed by the IAEA about the discrepancy and assisted to understand and resolve the discrepancies.

The aim of the TLD audits in dosimetry for SSDLs is to check the implementation of a dosimetry code of practice in order to assure proper dissemination of dosimetry standards to the end-users, e.g. radiotherapy hospitals. The TLD audits involve the checking of radiation beam calibration and analysis of the dosimetry procedures applied by the SSDLs.

As mentioned above, the combined relative standard uncertainty of the TLD system for radiotherapy is estimated to be 1.7% (\(k=1\)), when both the IAEA and the participating institute use the same method to derive the absorbed dose to water. Based on these values, the acceptance limits for the TLD audits for the SSDLs are set at \(\pm 3.5\%\), and they define the maximum discrepancy between the stated and the measured doses which does not require any corrective actions.

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The IAEA/WHO TLD audits for hospitals are conducted to ensure the accuracy and consistency of radiation dosimetry in radiotherapy. The purpose of these audits is to provide an independent verification of the dose delivered by treatment machines in radiotherapy hospitals. At the beginning of the programme, the TLD programme was offered to both developing and developed countries. At present, the IAEA/WHO TLD programme is offered only to radiotherapy hospitals in developing countries for whom this programme is available.

The results of this programme for 52 SSDLs participating in the TLD audits in 2000 are given in Figure 4, where the ratios of the dose determined by the IAEA from the TL response to that stated by the SSDL are given for $^{60}$Co and high-energy X rays. Each data point corresponds to the average of three dosemeters. Out of 79 beam calibrations checked in 2000, one deviation was detected which was outside the acceptance limits of ±3.5%. The audit results indicate that the consistency in the basic dosimetry of the SSDLs is satisfactory.

**TLD AUDITS FOR RADIOTHERAPY HOSPITALS**

The main purpose of the TLD postal dose audit programme for dosimetry in radiotherapy is to provide an independent verification of the dose delivered by treatment machines in radiotherapy hospitals. At the beginning, the TLD programme was offered to both developing and developed countries. At present, the IAEA/WHO TLD programme is offered only to radiotherapy hospitals in developing countries for whom this is the only opportunity to participate in an external audit programme.

The results are sent to participants through the WHO channels. Information is provided on the participant’s stated dose, the IAEA TLD-determined dose, the relative deviation and the ratio of the TLD-determined to the participant’s stated doses. The acceptance limits of the IAEA/WHO TLD audits for hospitals are ±5%.

![Figure 4. Results of the IAEA/WHO TLD postal dose audits of SSDLs for the delivery of dose to water under reference conditions for the TLD runs organised in 2000. Data in the graph correspond to the ratio of the IAEA-determined dose from the TL response ($D_{TLD}$) to that stated by the SSDL ($D_{stat}$). Each data point corresponds to the average of three dosemeters. A total of 79 beam calibrations were checked in 56 laboratories, which include 52 $^{60}$Co (circles) and 27 high-energy X ray beams (triangles). One deviation was found outside the acceptance limits of ±3.5%.

![Figure 5. Distribution of the results of the IAEA/WHO TLD postal dose audits of radiotherapy hospitals for the delivery of absorbed dose to water under reference conditions during 1969–2000. Data in the graph correspond to ratios of the IAEA’s determined dose ($D_{TLD}$) relative to the dose stated by the hospital ($D_{stat}$). Each data point corresponds to the average of three dosemeters (two after 1998). A total of 3995 beam calibrations were checked in 1118 hospitals. The mean distribution is 1.013 and the standard deviation is 9.0%. The deviations vary between a minimum $D_{TLD}/D_{stat}$ ratio of 0.170 and a maximum of 2.188. Only 70% of the global results are within the acceptance limits of ±5%.

These limits correspond approximately to the expanded relative standard uncertainty of the IAEA TLD system ($u_r = 2.3\%$ and $k = 2$). The acceptance limits of ±5% follow the ‘classical’ tolerance value given by ICRU Report 24.

In the period 1969–2000, 1118 hospitals in 112 countries in Africa, the Eastern Mediterranean, Europe, Latin America, South-East Asia and the Western Pacific participated in the IAEA/WHO TLD postal dose audits. The global results of 3995 beam output checks performed in this period are shown in Figure 5. They include 3342 results for $^{60}$Co beams and 653 results for high-energy X rays. They are expressed as ratios of the TLD measured (IAEA) to stated (user) doses $D_{TLD}/D_{stat}$. Each value in the graph represents the average of three TL dosemeters (since 1998 the average has been for two dosemeters). The mean of the distribution is 1.013 and the standard deviation is 9.0%. The deviations vary between a minimum $D_{TLD}/D_{stat}$ ratio of 0.170 and a maximum of 2.188. Only 70% of the global results are within the acceptance limits of ±5%.

During the past three years, the percentage of the deviations within the acceptance limits has increased to 82%. All results outside the acceptance limits were followed up. Many participants improved their results in the follow-up irradiation (60% results), but still 20% of the results remain outside the acceptance limits.
the discrepancies persisted. Regrettably, 20% of the follow-up TLDs have not been returned to the IAEA for evaluation. Five site visits by the IAEA experts were organised to 11 hospitals where dosimetry practices were revised and recommendations to the local staff provided. Until the recommended changes have been implemented to ensure that the deviations do not recur, there might be major problems with the delivery of precise radiation dosages to patients at these hospitals.

In 1998–2000, 385 radiotherapy facilities in 277 hospitals, mainly from Eastern Europe and Asia, which had never been audited before, were included in the IAEA/WHO TLD programme. Only 74% of the results of a first participation are within the ±5% limits, while 89% of the users that have benefited from a previous TLD audit are successful. The large discrepancies observed in some hospitals can be attributed mainly to insufficient professional training of the hospital staff, but also to obsolete radiotherapy machines and inappropriate dosimetry equipment.

It is of interest to mention that the distribution of the results for 50 high-energy X-ray beams audited in Australia in 1998 had a mean of 1.002 and a standard deviation of 1.1%, with no results outside the acceptance limits of ±5% (11).

CONCLUSION

The IAEA/WHO TLD postal programme for radiotherapy level dosimetry has been strengthened with new procedures and equipment that improve the overall efficiency of the programme. Due to the automation of the TLD system and the development of computerised tools for dose calculation from the readings, the IAEA has substantially increased its capacity and doubled the annual number of TLD audits.

The IAEA maintains a strict quality control of the TLD system calibration through regular checks of the reproducibility in dose determination with TLDs using an internal verification (self-tests) and external audits with BIPM and two PSDLs. In addition to the PSDLs, the international and national TLD networks and a few advanced radiotherapy hospitals exchange reference irradiations with the IAEA, acting as a reciprocal external quality control of the experimental component of the programme.

The IAEA/WHO TLD postal dose quality audit service monitors the performance of the SSDLs in the therapy dose range by providing approximately 80 beam checks per year. This programme demonstrates good consistency in the basic dosimetry worldwide with more than 95% SSDLs having the TLD audit results within the ±3.5% acceptance limits.

The TLD programme for hospitals has checked approximately 4000 clinical beams in over 1100 hospitals, and in many instances significant errors have been detected in the beam calibration. Subsequent follow-up actions have helped the radiotherapy centres to resolve the discrepancies and to correct the dosimetry procedures, thus preventing further mistreatment of patients.

The significance for a hospital to participate regularly in external audits to reach and maintain an adequate level of dosimetry has been observed. Typically, only 74% of the hospitals that receive TLD for the first time have results within the acceptance limits (±5%), while 89% of the institutions participating regularly in the audits have results within the ±5% limits.

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