The IAEA/WHO TLD postal dose quality audits for radiotherapy: a perspective of dosimetry practices at hospitals in developing countries

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Abstract

Background and purpose: The IAEA/WHO TLD postal programme for external audits of the calibration of high-energy photon beams used in radiotherapy has been in operation since 1969. This work presents a survey of the 1317 TLD audits carried out during 1998–2001. The TLD results are discussed from the perspective of the dosimetry practices in hospitals in developing countries, based on the information provided by the participants in their TLD data sheets.

Materials and methods: A detailed analysis of the TLD data sheets is systematically performed at the IAEA. It helps to trace the source of any discrepancy between the TLD measured dose and the user stated dose, and also provides information on equipment, dosimetry procedures and the use of codes of practice in the countries participating in the IAEA/WHO TLD audits.

Result: The TLD results are within the 5% acceptance limit for 84% of the participants. The results for accelerator beams are typically better than for Co-60 units. Approximately 75% of participants reported dosimetry data, including details on their procedure for dose determination from ionisation chamber measurements. For the remaining 25% of hospitals, who did not submit these data, the results are poorer than the global TLD results. Most hospitals have Farmer type ionisation chambers calibrated in terms of air kerma by a standards laboratory. Less than 10% of the hospitals use new codes of practice based on standards of absorbed dose to water.

Conclusion: Despite the differences in dosimetry equipment, traceability to different standards laboratories and uncertainties arising from the use of various dosimetry codes of practice, the determination of absorbed dose to water for photon beams typically agrees within 2% among hospitals. Correct implementation of any of the dosimetry protocols should ensure that significant errors in dosimetry are avoided.

Keywords: Quality assurance; Postal dose audits; TLD audits; Dosimetry practices at hospitals

1. Introduction

The IAEA/WHO TLD postal programme for external audits of the calibration of high-energy photon beams used in radiotherapy has been in operation since 1967 [3,6,16,18,19]. The programme aims at improving the accuracy and consistency of clinical dosimetry in radiotherapy hospitals worldwide. In its early years, the TLD service was offered to hospitals both in developing and industrialized countries, but at present it is provided mainly to institutions in developing countries. For these hospitals the IAEA/WHO TLD programme is practically the only opportunity to participate in an external audit programme. TLD audits for radiotherapy dosimetry are also offered to the Secondary Standards Dosimetry Laboratories (SSDLs) [4,20] that disseminate dosimetry standards to end-user institutions by calibrating their local reference dosimeters for use in radiotherapy. Initially, the TLD audits were provided for Co-60 beams only, but since 1991 high-energy X-ray beams from clinical accelerators have also been included in the service.

The IAEA has introduced recently substantial modifications in the technical and operational aspects of the TLD programme, including the organisation of a comprehensive computerised database. In addition to the administrative data and results of the audits, the database includes information provided by the users on their beam output measurements, the dosimetry system used for the measurements, the geometry of the TLD irradiation, and the values of the different quantities and correction factors required for...
the dose determination in reference conditions following a dosimetry protocol or code of practice.

This work presents a survey of the 1317 TLD audits carried out during 1998–2001. The main difference with previous publications on this topic is that, on this occasion, the results are discussed from the perspective of the dosimetry practices in hospitals in developing countries, based on the information provided by the users in their TLD data sheets, as registered in the database. This is of interest considering the introduction of the new international code of practice for radiotherapy dosimetry based on radiation metrology standards of absorbed dose to water, IAEA TRS-398, published in 2000 [12].

2. Calibration of the IAEA TLD system

The IAEA TLD system has been described previously [16]. The calibration of the system is derived from the ionisation chamber measurements of the absorbed dose to water at the position of the TLD. A NE 2561 secondary standard ionisation chamber calibrated by the International Bureau of Weights and Measures (BIPM) was used. Before 2000 the chamber calibration was in terms of air kerma and the dose to water was determined using the IAEA TRS-277 code of practice [9]. From the beginning of 2000 the absorbed dose was determined using a chamber calibrated in terms of absorbed dose to water, also traceable to the BIPM, and the IAEA TRS-398 code of practice [12].

The quality assurance (QA) of the IAEA TLD system includes quality control reference irradiations provided by the BIPM, some Primary Standard Dosimetry Laboratories (PSDL), and a few reference radiotherapy centres. The results of the reference irradiations provided during 1998–2001 by the BIPM and three PSDLs [the Bundesamt für Eich- und Vermessungswesen (BEV) in Austria, the Physikalisch-Technische Bundesanstalt (PTB) in Germany and, recently, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in Australia] are shown in Fig. 1. The graph gives ratios of the absorbed dose as determined by the IAEA and that stated by the BIPM or the PSDL, \( D_{IAEA}/D_{PSDL} \). The results of 59 reference irradiations are shown. In 1998–1999 the mean of the distribution was 0.998 and the standard deviation was 0.6%, whereas in 2000–2001, these were 1.004 and 0.9%, respectively. Although the increase of the mean by 0.6% is not significant statistically, it probably results from the change of the TLD system calibration, which is now based on the absorbed dose to water rather than air kerma. All data in Fig. 1 fall between 0.982 and 1.016.

3. Irradiation of the TLD at hospitals

Hospitals are requested to irradiate the TLD in a water phantom, in the same way as a patient would be irradiated using a source-skin-distance (SSD) or an isocentric (SAD) set up, depending on the normal practice at a hospital. The dose delivered to the TL dosimeters should be calculated in the same way as for patient treatments, i.e. using routine clinical data. The TLD irradiation is to be performed either by medical personnel (radiotherapy technologists) or, if available, by a medical physicist. They are requested to report, in the TLD data sheet, data of the treatment unit including the beam output, as used clinically. The details of an ionisation chamber determination of the dose or the dose rate may be made following the TLD irradiation, if the hospital has a medical physicist and dosimetry equipment available.

4. Results of the TLD irradiations

Over a period of more than 30 years, the IAEA/WHO TLD programme has verified the calibration of more than 4300 photon beams in approximately 1200 radiotherapy hospitals [3,6,16,18,19,20]. During 1998–2001 the number of beams checked was 1317, which corresponds to approximately 30% of the total. These were made in 584 hospitals of 83 countries in Africa, eastern Mediterranean, Europe, Latin America and the Caribbean, south-east Asia and the western Pacific. The distribution of the number of beams checked per region is shown in Fig. 2. The participation from the different regions is governed by the requests received at the different regional offices of the WHO; for example, 35% of the beams checked were in...
hospitals of Latin America whereas only 6% were in Africa. After 1996, the IAEA/WHO TLD audits have been initiated in some countries of eastern and south-eastern Europe (e.g. Armenia, Bosnia-Herzegovina, Estonia, Latvia, Lithuania, FYR Macedonia, Ukraine, Russia and Yugoslavia), raising the number of beams checked in Europe to 31%. A single TLD batch was provided in 1998, on special request, to hospitals in Australia [7].

The distribution of the results for 1998–2001 is shown in Fig. 3; they include 791 Co-60 beams and 526 high-energy X-ray beams. The results correspond to ratios of the IAEA TLD measured dose to that stated by the user, $D_{TLD}/D_{stat}$. Each value represents the average of two TL dosimeters. The mean of the distribution is 1.010, its standard deviation 7.2%, and the outliers range between a minimum of 0.166 and a maximum of 1.995. In 84% of the cases, the results were within the IAEA acceptance limit of 5% [2], whereas 1.3% (17 beams) had discrepancies larger than 20%, pointing to major problems in the delivery of dose to the TLD. All results outside the 5% acceptance limit were followed up with a second, blind participation, where participants were not informed of the size of the discrepancy discovered in the first run. The majority of participants improved their results in the second irradiation so as, after the correction, the percentage of acceptable results increased to 93%. Unfortunately, the remaining 7% of poor audit results could not be resolved. This was due either to a persistent error or to failure in responding to the efforts by the IAEA to help resolve the problem. On-site visits were organized to 14 hospitals where dosimetry practices were revised and recommendations were provided to the local staff. 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. It is important to note that the distribution of the results for 50 high energy X-ray beams audited in Australia in 1998 had a mean ratio of 1.002 and a standard deviation of 1.1%, with no results outside the acceptance limit of 5% [7].

5. Analysis of the information provided by hospitals in TLD data sheets

A detailed analysis of the information provided by the participants in their TLD data sheets is systematically performed at the IAEA with the aim of verifying the participant’s calculation of the dose delivered to the TLD. Any discrepancy between the dose as calculated by a participant and that calculated by the IAEA using the participant’s data, is also investigated. This analysis of the data sheets helps to trace the source of any discrepancy between the TLD measured dose and the participant stated dose, provided relevant information is supplied.

Of the 1317 data sheets submitted by participants and analysed, 75% reported data, at least partially, pertinent to the dosimetry procedure used for the determination of the dose given to TLD based on an ionisation chamber measurements. Since the request for providing beam measurement details is optional, and pertinent to the dosimetry procedure used for the determination of the dose given to TLD based on an ionisation chamber measurements. Since the request for providing beam measurement details is optional, and addressed to medical.

1 The mean of the results distribution of 1.010 differs from 1.000 by 1%. As the IAEA TLD system has been verified by BIPM and PSDLs, this difference may be attributed to the differences in dosimetry equipment, traceability to different standards laboratories and uncertainties arising from the use of various dosimetry codes of practice by hospitals worldwide.

2 The acceptance limit of the TLD audits defines the maximum discrepancy between stated and measured doses, which does not require further investigation.
physicists only, it is assumed that the remaining 25% who did not submit these data probably correspond to centres without physicists or where dosimetry equipment is not available. Such hospitals are typically small centres equipped mostly (80%) with Co-60 units. Only 73% of their results fall within the acceptance limit of 5%, which is significantly lower than the global percentage (84%) of the acceptable results. Sixty percent of the centres submitting insufficient dosimetry information are from Latin America. In contrast, 87% of the results are within the 5% limit for the hospitals submitting the dose measurement data. The machines checked in this group are in equal proportion Co-60 units (54%) and accelerators (46%). The results for accelerator beams are typically better than for Co-60 units in all groups.

6. Irradiation time

Information analysed for 178 Co-60 beams checked in 1998–1999 enabled a study of the irradiation time required for the delivery of 2 Gy to a ‘tumour’ with its centre (a TLD) at a depth of 5 cm. The irradiation times were recalculated to 1 January 2000 using the actual dose values measured with the TLD. The relevant distribution is given in Fig. 4. An average time of 3.9 min was used to deliver 2 Gy at 5-cm depth with a field size of 10 × 10 cm², at the SSD (or SAD), as reported in the data sheets, but in many instances the irradiation time exceeded 10 min. Excessively long irradiation times used for patient treatment may compromise the demand for high precision on dose delivery to a tumour site. It is well known that patient irradiation times should be kept reasonably short, otherwise patient immobilisation cannot be guaranteed and the natural organ movements increase the uncertainty in the positioning of the volume to be irradiated. This may lead to an increased uncertainty in dose delivery, resulting in a reduction of the probability of a successful treatment and an increased patient morbidity rate.

Although recommendations for the output of new Co-60 therapy machines have been issued[10], there are at present no international recommendations on the minimum acceptable dose rate delivered by a Co-60 therapy unit or on the maximum time used to deliver a single irradiation session. A French regulation exists[8] on the activity of Co-60 sources acceptable for radiotherapy where the minimum dose rate in air at the distance of 100 cm must be at least 13 Gy/h. This is equivalent to approximately 0.3 Gy/min for a typical irradiation geometry (80 cm SAD, 10 × 10 cm² field size, 5-cm depth). Twenty-five out of the 178 Co-60 units audited (14%) had a dose rate below this recommendation.

7. Equipment availability

As already mentioned, 75% of the data sheets contained at least partial information on the equipment and dosimetry procedures used to determine the dose delivered to the TLD sets. Table 1 shows the distribution of ionisation chamber models reported by 958 participants, where 73% were 0.6 cm³ Farmer-type chambers from well-known manufacturers, such as Nuclear Enterprises or PTW. It is interesting to note that 14% of the participants calibrate high-energy photon beams with small waterproof chambers of 0.1–0.3 cm³, designed for relative measurements. Almost 5% of the ionisation chambers were manufactured locally, especially in China and India, and the remaining 8% were chambers of obsolete design, intended for in-air measurements. Many of the latter type are the old ‘Vakutronik’ chambers, manufactured in the former Eastern Germany and still in use in some countries of eastern Europe.

The statistical data, i.e. the mean and standard deviation of the distribution of the TLD results according to the ionisation chamber types used for beam calibration, in terms of the ratios of the IAEA measured dose to the user stated dose, $D_{\text{TLD}}/D_{\text{stat}}$, is also included in Table 1. It is clear that the results for users having modern 0.6 cm³ ionisation chambers exhibit smaller spread than those for users with old or non-typical equipment. Moreover, approximately 93% of the results for hospitals with Farmer-type chambers were within the 5% acceptance limit, whereas for the group using obsolete or locally manufactured equipment this figure was reduced to 61%. The mean value of the distributions does not change significantly, however, it shows differences of up to 1% between different groups.

The results for users having Farmer-type chambers were also analysed with respect to the manufacturers. The spread...
of the results was similar for chambers manufactured by both NE and PTW, with standard deviations of 3.3% and 3.4% and mean values of 1.006 and 1.009, respectively.

### 8. Calibration of equipment

Approximately 98% of the users reporting dosimetry data indicated a calibration factor of the ionisation chamber used, although only 88% were able to identify if the type of factor was in terms of absorbed dose to water ($N_{D,w}$), air kerma ($N_K$) or exposure ($N_X$). In 78 data sheets (9%) users confused the symbol $N_{D,w}$ with the symbol $N_D$ (absorbed dose to air chamber factor), which was used in the 1987 edition of the TRS-277 protocol [9] and was replaced later by the symbol $N_{D,air}$ in the TRS-381 code of practice [11]. The $N_{D,w}$ and $N_{D,air}$ factors differ mainly by the value of the water/air stopping power ratio for Co-60 (1.133), and the confusion resulted in errors of approximately 10–13%, depending on the photon beam quality. Most hospitals were used to $N_K$ or $N_X$ factors, from which they derive $N_{D,air}$, but they were not yet familiar with the $N_{D,w}$ factor. Unfortunately, some manufacturers and a few calibration laboratories in some developing countries have disseminated $N_{D,w}$ calibrations without a proper explanation of their use.

Table 2 gives the percentage of hospitals using ionisation chambers with calibration factors in terms of absorbed dose to water ($N_{D,w}$), air kerma ($N_K$) or exposure ($N_X$) as reported in 918 data sheets. Approximately 50% of the chambers had been calibrated in terms of air kerma, 29% in terms of exposure and 12% in terms of absorbed dose to water. Eight percent of users did not identify what standard was used for the chamber factors. The percentage of calibrations done in terms of absorbed dose to water has increased from 10% in 1998–1999 to 15% in 2000–2001.

The statistical evaluation of the distribution of the results (the mean and the standard deviation of the distribution of $D_{TLD}/D_{air}$) for groups with different types of ionisation chamber calibration factors is also given in Table 2. The distribution of results pertaining to ionisation chamber calibrations in terms of $N_{D,w}$ exhibits a smaller standard deviation (2.8%) than for the other calibration types, where the standard deviations are up to 4.0%. The mean values of the distributions for the different groups are: 1.002 for $N_K$, 1.011 for $N_{D,w}$, 1.014 for $N_X$ and 1.016 for unknown calibration types. The ionisation chamber calibrations in terms of absorbed dose to water have mainly been provided by PTW, and are traceable to the primary standard of absorbed dose to water developed by PTB. The differences in the mean of the distribution are consistent with the differences between the primary standards for absorbed dose to water at the BIPM and PTB [12].

In addition to other dosimetry data, physicists were requested to report the date of the last calibration of their dosimetry equipment by a standards laboratory. Based on 742 data sheets that provided this information: 70% of the ionisation chambers had been calibrated within the previous 2 years, whereas 10% of the chamber calibration certificates were at least 4 years old.

### 9. Dosimetry procedures

More than 80% of the participants reporting dosimetry data provided information on the dosimetry protocol used, including numerical values of the correction factors and interaction coefficients applied for the calculation of absorbed dose to water from ionisation chamber measurements.

Some participants did not report the dosimetry protocol used, but provided information on their dose calculation procedures. In most of these cases users followed the recommendations of ICRU-14 published in 1969 [13]. However, they could not identify the origin of the coefficients they used for the calculation of the dose. The ICRU-14 recommendations were widely accepted and adopted by many countries in the 1970s and even if these should have now mainly a historical value, the old procedures and coefficients once incorporated to the routine measurement protocols were still in use in these hospitals.

### Table 1

<table>
<thead>
<tr>
<th>Ionisation chamber type</th>
<th>0.1–0.3 cm³</th>
<th>Farmer type</th>
<th>Obsolete type</th>
<th>Local make</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of checks</td>
<td>138</td>
<td>698</td>
<td>76</td>
<td>46</td>
</tr>
<tr>
<td>(Percentage of checks)</td>
<td>(14%)</td>
<td>(73%)</td>
<td>(8%)</td>
<td>(5%)</td>
</tr>
<tr>
<td>Mean $D_{TLD}/D_{air}$</td>
<td>1.006</td>
<td>1.007</td>
<td>1.015</td>
<td>1.012</td>
</tr>
<tr>
<td>1 S.D.</td>
<td>3.7%</td>
<td>3.3%</td>
<td>6.9%</td>
<td>5.1%</td>
</tr>
</tbody>
</table>


### Table 2

<table>
<thead>
<tr>
<th>Ionisation chamber calibration factor</th>
<th>$N_{D,w}$</th>
<th>$N_K$</th>
<th>$N_X$</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of checks</td>
<td>114</td>
<td>457</td>
<td>270</td>
<td>77</td>
</tr>
<tr>
<td>(Percentage of checks)</td>
<td>(12%)</td>
<td>(51%)</td>
<td>(29%)</td>
<td>(8%)</td>
</tr>
<tr>
<td>Mean $D_{TLD}/D_{air}$</td>
<td>1.011</td>
<td>1.002</td>
<td>1.014</td>
<td>1.016</td>
</tr>
<tr>
<td>1 S.D.</td>
<td>2.8%</td>
<td>3.7%</td>
<td>4.3%</td>
<td>3.9%</td>
</tr>
</tbody>
</table>

Table 3 shows the percentage of hospitals reporting the use of $N_X$ based dosimetry protocols, such as ICRU-14 [13] or equivalent national protocols, $N_K$ based protocols, such as IAEA TRS-277 [9], AAPM TG-21 [1] or NCS-2 [17], and new absorbed dose to water ($N_{D,w}$) protocols, mainly the German DIN-6800 [5], the IAEA TRS-398 [12] or AAPM TG51 [2]. Approximately 65% of the users applied $N_K$ based protocols, mainly TRS-277, whereas 10% of the participants reported using the old $N_K$ formalism; another 7% were based on the modern $N_{D,w}$ based dosimetry procedures. The remaining 18% of users, who did not identify a dosimetry protocol, followed predominantly the old $N_K$ based procedure. The use of new $N_{D,w}$ based protocols increased from 2% in 1998–1999 to 12% in 2000–2001. Most physicists using IAEA TRS-277 or AAPM TG-21 derived the absorbed dose to air calibration factor (or the cavity gas calibration factor in TG-21) from an $N_K$ calibration factor, but many did use a conversion from an exposure calibration factor (compare Table 2). As mentioned earlier, some hospitals have received $N_{D,w}$ calibration of their ionisation chambers without the accompanying $N_{D,w}$ based dosimetry protocol, hence the difference in the figures reported in Tables 2 and 3.

The statistical evaluation of the distribution of results (in terms of $D_{TLD}/D_{act}$) for hospitals using different dosimetry protocols is also given in Table 3. The results based on $N_{D,w}$ protocols show smaller standard deviation (2.2%) than the results based on $N_K$ protocols (3.3%), whereas the groups based on $N_X$ and on ‘unknown’ protocols have standard deviations exceeding 5%. The mean of the distributions for the different groups varies from 1.004 ($N_K$ based protocols) to 1.023 (local old $N_X$ based protocols). These results are consistent with the previous observations on the differences arising from ionisation chamber calibrations in terms of exposure, air kerma and absorbed dose to water (see Table 2). They are also consistent with the adoption of different protocols that differ slightly in their recommended measuring procedures and in the numerical values of interaction coefficients and correction factors for commonly used ionisation chambers. Since prior to 2000 the IAEA calibration of its TLD system was based on the $N_K$ formalism of TRS-277, the mean value (1.004) for hospitals using $N_K$ based dosimetry protocols is much closer to unity than for the $N_X$ and $N_{D,w}$ groups. The results for 17 hospitals with deviations outside 20% have been excluded from this statistical analysis.

Of special interest is the survey of the 50 data sheets completed by Australian hospitals in 1998. All medical physicists in Australia use a national protocol based on the IAEA TRS-277 code of practice. The ionisation chambers used are predominantly NE 2571, with calibrations provided by the national PSDL (ARPANSA) in terms of air kerma. The detailed reports submitted on the dosimetry procedures, including coefficients and factors for the dose calculation, demonstrate a thorough understanding of the protocol applied. This good level of professional training and high degree of uniformity in dosimetry practices at the national level have been demonstrated by the excellent TLD results achieved in 1998 [7].

10. Conclusions

A survey of 1317 results obtained in the IAEA/WHO TLD postal dose audit programme during 1998–2001 has been performed with emphasis on the information submitted in the data sheets by participating hospitals. Approximately 75% of participants reported, at least some dosimetry data, including details on their procedure for dose determination from ionisation chamber measurements. It seems that the remaining 25% of hospitals, which did not submit these data, may not have physicists or dosimetry equipment available. Their results are poorer than the global TLD results.

The condition of the Co-60 units in some hospitals in developing countries exhibits performance deficiencies due to poor technical shape caused by inadequate maintenance or too low activity of a Co-60 source. The irradiation time required for the delivery of 2 Gy is often excessively long and this may result in loss of precision of the dose delivery to a tumour site due to patient immobilisation and natural organ motions.

The dosimetry protocols used by participants [1,2,5,9,12,13,17] differ slightly in their recommended measurement procedures and in the numerical values of coefficients and correction factors, resulting in lack of consistency in the dose delivered to TLD by different hospitals. The variety of makes and models of ionisation chambers available at hospitals and the different types of calibration factors, traceable to different standards laboratories, introduce additional uncertainties in dosimetry measurements among hospitals. Despite these differences, on average, the agreement in the determination of absorbed dose to water for photon beams using different protocols was on most occasions within 2%. Correct implementation of any of the dosimetry protocols [1,2,5,9,11,12,13,14,17] and the use of a consistent set of coefficients and correction factors should therefore ensure that significant errors in dosimetry are avoided, provided
the equipment used conforms to modern standards. On the other hand, a number of hospitals participating in the IAEA/WHO TLD postal dose audits have to revise their dosimetry procedures and upgrade their instrumentation to comply with the demands of modern radiotherapy dosimetry and to prevent radiological accidents [15].

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References


