Postal dose audits for radiotherapy centers in Latin America and the Caribbean: trends in 1969–2003

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SYNOPSIS

Since 1969 the International Atomic Energy Agency and the World Health Organization (along with the Pan American Health Organization, working with countries in Latin America and the Caribbean) have operated postal dosimetry audits based on thermoluminescent dosimetry (TLD) for radiotherapy centers. The purpose of these audits is to provide an independent dosimetry check of radiation beams used to treat cancer patients. The success of radiotherapy treatment depends on accurate dosimetry. Over the period of 1969 through 2003 the calibration of approximately 5 200 photon beams in over 1 300 radiotherapy centers in 115 countries worldwide was checked. Of these audits, 36% were performed in Latin America and the Caribbean, with results improving greatly over the years. Unfortunately, in several instances large TLD deviations have confirmed clinical observations of inadequate dosimetry practices in hospitals in various parts of the world or even accidents in radiotherapy, such as the one that occurred in Costa Rica in 1996. Hospitals or centers that operate radiotherapy services without qualified medical physicists or without dosimetry equipment have poorer results than do hospitals or centers that are properly staffed and equipped. When centers have poor TLD results, a follow-up program can help them improve their dosimetry status. However, to achieve audit results that are comparable to those for centers in industrialized countries, additional strengthening of the radiotherapy infrastructure in Latin America and the Caribbean is needed.

Since 1969 the International Atomic Energy Agency (IAEA), in conjunction with the World Health Organization (WHO) (and the Pan American Health Organization (PAHO), working with countries in Latin America and the Caribbean), has operated a program to validate the calibration of radiotherapy beams used for the treatment of cancer patients with radiation therapy (1–6). Using thermoluminescence dosimeters (TLDs), this IAEA/WHO program provides an independent verification or a quality assurance (QA) audit of the dose delivered by radiotherapy treatment machines. Independent external quality audits are widely recognized as an effective method for verifying that the quality of dosimetry practice in a radiotherapy center is appropriate. Precise clinical dosimetry is essential to maximize the probability of success in cancer therapy using radiation, which demands knowing the exact radiation dose delivered to the patient's tumor. The IAEA/WHO TLD program aims at improving the accuracy and consistency of clinical radiotherapy dosimetry worldwide.

In 1991 the program was expanded to include high-energy photon beams from medical linear accelerators, in addition to those produced by cobalt-60 machines. Through this program the IAEA has also monitored the performance of secondary standards dosimetry laboratories since 1981 (7, 8). (Secondary standards dosimetry laboratories (SSDLs) are national laboratories that maintain secondary-standard-class dosimetry systems and that calibrate dosimetry instruments that are used for beam output measurements at radiotherapy centers.) The audits are coordinated with national audit networks operating in several countries, and with organizations that provide dose audits in industrialized countries (5).

The operation of the TLD program is carried out through close collaboration among the IAEA, WHO, and PAHO. Based on the requests collected by WHO and PAHO, the IAEA prepares packages with TLDs for radiotherapy centers. Each center receives two TLDs for irradiation. TLDs are in the form of capsules 2.5 cm long and 0.5 cm in diameter. They are accompanied by instructions for their irradiation, data sheets for reporting doses, and special TLD holders. WHO and PAHO distribute TLD packages to radiotherapy centers, where they are irradiated by hospital staff and returned through WHO or PAHO to the IAEA for evaluation. The dose given to the dosimeters is determined at the IAEA's Dosimetry Laboratory, and the result is compared with the dose stated by the hospital staff.

Centers are requested to irradiate the TLD using a special holder that is placed in a tank filled with water. The holder has an opening for the TLD, with the TLD being placed at a depth of 5 cm in the water. The irradiation should be done in the same way as for a patient with a tumor located at a depth of 5 cm, following the normal practice at the center and calculating the dose to the TLD the same way as for patient treatments (i.e., using routine clinical data). The TLD irradiation is to be performed either by a medical physicist, if one is available, or by other medical personnel. In the TLD data sheet the participants report data related to the treatment machines, such as the machine model, its date of installation, and the beam parameters, including the beam output as used clinically. Determination of the dose measured with an ionization chamber may be made following the TLD irradiation if the hospital has a medical physicist and dosimetry equipment available. The beam output is then calculated following a dosimetry code of practice (dosimetry protocol), and the details of the procedure are reported on the data sheet.

Discrepancies of less than 5% between the participant-stated dose and the TLD-measured dose are considered acceptable. This 5% acceptance limit defines the maximum discrepancy between stated and measured doses that does not require any further investigation. For centers with results outside the 5% acceptance limit, the IAEA has established a follow-up program that uses a second TLD check to give centers a chance to correct the discrepancy. However, if the follow-up TLD check is still unsuccessful and the errors cannot be resolved through communication with the center or by the national SSDL, on-site visits by IAEA experts in radiotherapy physics are organized to help identify and rectify the dosimetry problems.

The information that participants provide on the TLD data sheets is systematically analyzed at the IAEA. This is done in order to evaluate the status of calibration dosimetry, to trace the source of any discrepancies in the dose measurement and calculation, and to gain an understanding of the status of the use of different dosimetry equipment and procedures and various dosimetry codes of practice (protocols). Different dosimetry protocols are used in countries around the world, ranging from old exposure-based protocols of the early 1970s, through air kerma-based protocols developed in the 1980s, up to the recently-developed modern absorbed dose to water-based protocols.

This paper discusses the results of the IAEA/WHO TLD audits in Latin America and the Caribbean, taking into account the staffing and the availability and status of equipment and dosimetry practices in radiotherapy centers in those countries. The results from the TLD audits in Latin America and the Caribbean are compared with the results from other geographical regions of the world.

CALIBRATION AND QUALITY ASSURANCE OF THE IAEA TLD SYSTEM

The IAEA TLD system has been described previously (3). The calibration of the system is derived from ionization chamber measurements of the absorbed dose to water at the position of the calibration TLD. The calibration follows the IAEA TRS-398 code of practice for dosimetry in radiotherapy (9). The ionization chamber calibration is traceable to the International Bureau of Weights and Measures (*Bureau international des poids et mesures*, BIPM), which is an international organization that ensures worldwide uniformity of measurements and their traceability to the International System of Units (SI).

A thorough set of quality control procedures is maintained for the IAEA TLD system in order to ensure its high-quality operation. In addition to internal quality control by the IAEA Dosimetry Laboratory itself, external checks of the system's performance are carried out through a program of reference TLD irradiations provided by the BIPM and several primary standards dosimetry laboratories (PSDLs). (PSDLs maintain primary standards in dosimetry. Calibration of instruments by SSDLs is traceable to primary standards.) The IAEA also exchanges dosimeters and compares measurements with other TLD-based QA networks in Europe and the United States of America. One of those networks is the ESTRO Quality Assurance (EQUAL) network for radiotherapy, which was set up for the countries of the European Union. (ESTRO is the European Society for Therapeutic Radiology and Oncology). Another of the networks is the Radiological Physics Center (RPC), which operates in North America (5). These linkages ensure that the three international TLD networks operate at similar levels of performance, based on consistent standards. In addition, a few radiotherapy centers, from different world regions, that have good records in dosimetry provide reference TLD irradiations for the IAEA, using their clinical beams. The reference irradiations by these reference institutions are synchronized in time with TLD irradiations by radiotherapy centers so that the consistency of the TLD measurements is assured for each TLD run organized by the IAEA for the centers.

The reference TLD irradiation program mentioned in the paragraph above has been carried out by the IAEA since 1997. The results of 116 irradiations by the BIPM and PSDLs during 1997–2003 showed that the IAEA TLD system performed very well. The mean of the distribution of the ratio of the IAEA's determined doses to the doses stated by the BIPM or the PSDL was 1.001, with a standard deviation of 0.008, and with all the data falling between 0.982 and 1.025. Similar to the results with the reference irradiations performed by the BIPM and the PSDLs, 260 results from the irradiations provided by the major TLD networks and reference centers showed very good international consistency in the measurement of doses for 1997 through 2003. The mean of the distribution was 1.001, the standard deviation was 0.011, and all the results fell between 0.953 and 1.033.

PARTICIPATION OF RADIOTHERAPY CENTERS IN THE IAEA TLD PROGRAM

Over the 34-year period of 1969 through 2003, the IAEA/WHO TLD program checked the calibration of 5 163 photon beams. The checks were made in 1 339 radiotherapy centers in 115 countries, in Latin America and the Caribbean (1 856 checks), the Western Pacific (1 099 checks), Europe (942 checks), Southeast Asia (632 checks), the Eastern Mediterranean (462 checks), and Africa (172 checks).

In Latin America and the Caribbean over that 1969–2003 period the 1 856 audits were conducted in 327 centers of 24 countries. These 1 856 audits comprised 36% of the 5 163 checks done around the world through the IAEA/WHO TLD program. The 1 856 figure included audits done at 73 centers in Argentina and Brazil, but those two countries later developed national TLD programs of their own and became independent of the IAEA/WHO services. The other 254 centers, in 22 countries of Latin America and the Caribbean, have continued to participate in the IAEA/ WHO TLD audits.

The respective numbers of audits in individual countries of Latin America and the Caribbean performed by IAEA/WHO in 1969–2003 varied from a few in Haiti to about 400 in Colombia. Some centers, especially newly-established ones, received TLDs only once, whereas others received TLDs up to 20 times for each beam. The number of beam checks in Latin America and the Caribbean started with 15 in 1969 and steadily increased in each subsequent decade, from approximately 220 beam checks in the 1970s, to approximately 400 in the 1980s, and to over 760 in the 1990s. For the 2000–2003 period there were 470 beam checks.

Close cooperation of the IAEA with WHO and PAHO has resulted in a systematic improvement in the return rate of irradiated TLDs from radiotherapy centers, from 60% to 70% in the early years to more than 90% at present. Currently, some geographical regions have a nearly perfect record for returning TLDs, whereas other regions are not as efficient. In some instances, due to problems with local mail services, the TLDs do not reach the centers. In other instances, the TLDs are received, but they are not irradiated and mailed back to the IAEA for analysis.

In Latin America and the Caribbean, the return rate of irradiated TLD batches has gradually improved, reaching the 95% level in 2002–2003. A disruption in the TLD distribution happened in Latin America and the Caribbean in 2001, when two batches of TLDs that two national TLD coordinators had ordered for local centers remained unirradiated due to organizational problems in these countries. These difficulties have now been resolved, and the centers in both countries have participated in TLD audits in subsequent years.

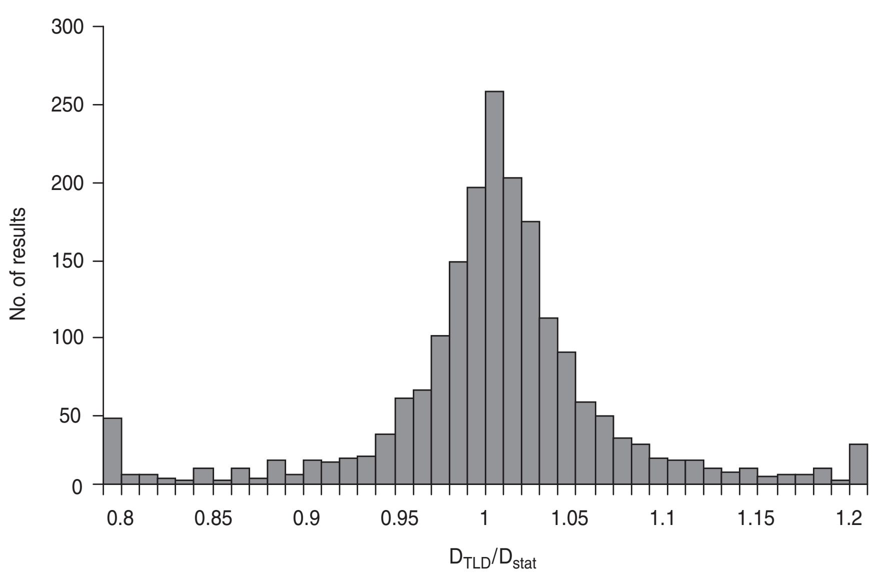
For participants around the world the typical time between the TLD irradiation and the return of irradiated TLDs through WHO or PAHO to the IAEA for analysis is about one to two months. The longest delay occurs during the collection of the irradiated TLDs by country coordinators, WHO regional offices, and PAHO. In Latin America and the Caribbean the average delay in returning the irradiated TLDs to the IAEA is approximately two months, with the delay generally in the range of one to three months, depending on the country. Unfortunately, in some countries, excessive delays are still too frequent. For example, in two countries of Latin America and the Caribbean, the delay in returning the TLD batches after the irradiation exceeded four months in 2000–2003. When errors in the radiotherapy beam calibration occurred, possibly resulting in inferior quality of patients' treatments, the errors remained unnoticed for prolonged periods. The number of patients' treatments potentially affected by poor dosimetry could be reduced if there were a more rapid resolution of the discrepancies.

RESULTS OF THE TLD AUDITS FOR RADIOTHERAPY CENTERS

Figure 1 shows the distribution of the 1 856 results in Latin America and the Caribbean for the 1969–2003 period. The histogram includes 1 458 checks of cobalt-60 (Co-60) beams and 398 checks of high-energy X-ray beams. The respective bars in the histogram indicate the ratio of the IAEA's determined dose (D_{TLD}) relative to the dose stated by the hospital (D_{stat}).

Table 1 compares the distribution of the TLD results for Latin America and the Caribbean with those for other geographical regions of the world. The table provides data for the entire 1969–2003 period as well as for just 2000–2003. As can be seen from the upper part of Table 1, the distribution of results in Latin America and the Caribbean for the period of 1969–2003 had a mean of 1.011 and a standard deviation of 0.095. The mean of the distribution of results of 1.011 differs from unity by 1.1%. As the IAEA TLD system has been verified by BIPM and PSDLs, this difference may be attributed to the differences in dosimetry equipment in radiotherapy centers and traceability of the dosimetry equipment calibration to different standards laboratories. The values include a minimum of D_{TLD}/D_{stat} = 0.00 (TLDs received no dose, although the data sheet indicated they had been irradiated) and a maximum of D_{TLD}/D_{stat} = 2.19 (by mistake, TLDs were irradiated twice). In 75% of the cases (1 388/1 856), the results were within the acceptance limit, whereas 4% (68/1 856) had major discrepancies (ones larger than 20%), indicating serious problems in dosimetry practices in those centers. In other geographical regions of the world the results were slightly better, with 78% of the checks (2 568/3 307) being successful in that same 1969–2003 period. In

FIGURE 1. Frequency distribution of the results of 1 856 IAEA/WHO thermoluminescent dosimetry (TLD) audits of radiotherapy centers in Latin America and the Caribbean, 1969–2003, for the ratios of the IAEA's determined dose (D_{TLD}) relative to the dose stated by the hospital (D_{stat})[a]



[a] The mean of the distribution was 1.011, and the standard deviation was 0.095. The minimum was 0.00 and the maximum 2.19. The two border bins show the results below 0.8 and above 1.2.

TABLE 1. Results of the IAEA/WHO thermoluminescent dosimetry (TLD) audits in Latin America and the Caribbean compared to those for other geographical regions of the world, for 1969–2003 and for 2000–2003

Period/Parameter	Latin America and the Caribbean	Other world regions	All regions
1969–2003			
Number of audits	1 856	3 307	5 163
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$ [a]	1.011	1.012	1.012
Standard deviation	0.095	0.075	0.083
Percentage of acceptable results[b]	75%	78%	77%
2000–2003			
Number of audits	470	1 073	1 543
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$ [a]	1.007	1.008	1.008
Standard deviation	0.085	0.072	0.076
Percentage of acceptable results[b]	87%	85%	86%

[a] $\frac{D_{TLD}}{D_{stat}}$ is the mean of the distribution of the TLD results expressed as ratios of the IAEA-determined dose (D_{TLD}) relative to the dose stated by the center (D_{stat}).
[b] The "acceptable" TLD results were those that were within a 5% limit of the TLD-measured to center-stated dose, i.e., $0.95 \leq D_{TLD}/D_{stat} \leq 1.05$.

2000–2003 the fraction of acceptable results in all regions increased compared to the results for the entire 1969–2003 period, with more noticeable improvement in Latin America and the Caribbean (increase from 75% to 87%) than in other regions (increase from 78% to 85%) (Table 1). These increases indicate an overall improvement in dosimetry practices in radiotherapy centers around the world.

Centers that have been regularly participating in the IAEA/WHO and other external dosimetry audits achieve better results than do institutions that are participating in an audit for the first time (5). In general, over the 2000–2003 period, only 78% of the radiotherapy centers in the world that received TLDs from the IAEA/WHO for the first time had results within the 5% acceptance limit, whereas 90% of the institutions participating regularly had acceptable results. The proportion of poor results with large deviations (beyond 10%) is also significantly higher for new centers than for those having participated in the audits previously. The difference between Latin America and the Caribbean and other world regions is that centers in Latin America and the Caribbean have a longer history of participating in the audits (see previous section, entitled "Participation of Radiotherapy Centers in the IAEA TLD Program"). Of the 470 beam checks performed in Latin America and the Caribbean in the 2000–2003 period, only 43 of them (9%) were from institutions participating in the IAEA/WHO program for the first time. In the same period in the other regions, 480 of the 1 043 beam checks (45%) were performed for centers participating for the first time. Compared with other regions of the world in the 2000–2003 period, fewer centers in Latin America and the Caribbean were first-time participants in the IAEA/WHO TLD program. That difference helps explain the fact that the percentage of acceptable results increased more in Latin America and the Caribbean during the last four years of that 1969–2003 period than it did in other parts of the world.

TLD RESULTS FOR THE COBALT-60 BEAMS AND THE HIGH-ENERGY X-RAY BEAMS FROM LINEAR ACCELERATORS IN 2000–2003

The 1 543 TLD results presented in the lower part of Table 1 consist of the checks of 837 Co-60 beams and of 706 high-energy X-ray beams from linear accelerators performed around the world in the 2000–2003 period. To gain a better understanding of the impact of basic radiotherapy infrastructure on the performance of radiotherapy centers in the TLD program, Table 2 analyzes the TLD results separately for Co-60 units and for linear accelerators, and it also compares the results in Latin America and the Caribbean with those for other world regions.

TABLE 2. Results of the IAEA/WHO thermoluminescent dosimetry (TLD) audits in Latin America and the Caribbean compared to those for other geographical regions of the world, for 837 Co-60 beams and 706 high-energy X-ray beams, 2000–2003

Beam/Parameter	Latin America and the Caribbean	Other regions	All regions
Co-60 beams			
Number of audits	242	595	837
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$[a]	1.006	1.010	1.008
Standard deviation	0.111	0.092	0.098
Percentage of acceptable results[b]	87%	78%	81%
Fraction of deviations beyond 10%	8%	10%	9%
High energy X-ray beams			
Number of audits	228	478	706
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$[a]	1.009	1.006	1.007
Standard deviation	0.041	0.035	0.037
Percentage of acceptable results[b]	85%	94%	92%
Fraction of deviations beyond 10%	4%	2%	2%

[a] $\frac{D_{TLD}}{D_{stat}}$ is the mean of the distribution of the TLD results expressed as ratios of the IAEA-determined dose (D_{TLD}) relative to the dose stated by the center (D_{stat}).
[b] The "acceptable" TLD results were those that were within a 5% limit of the TLD-measured to center-stated dose, i.e., $0.95 \le D_{TLD}/D_{stat} \le 1.05$.

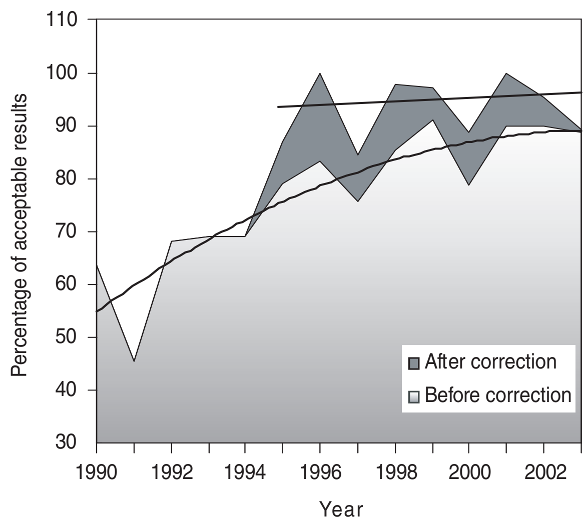
Overall, the results for all regions of the world (shown in the last column of Table 2) were better for X rays from linear accelerators than for Co-60 beams, with 92% (646/706) of results within the acceptance limit for high-energy X rays, versus 81% (674/837) for Co-60 beams. Similarly, large deviations (beyond 10%) for high-energy X rays occurred on 2% of occasions (17/706) versus 9% (76/837) for Co-60 beams. This is also reflected by the standard deviations of the distributions, which are 0.037 for high-energy X rays from linear accelerators and 0.098 for Co-60 beams.

In Latin America and the Caribbean, 66 deviations outside the 5% limit were detected in 470 checks, including 32/242 deviations (13%) for Co-60 beams and 34/228 deviations (15%) for high-energy X-ray beams. Although the occurrence of the deviations is approximately the same for Co-60 units and for medical linear accelerators, the spread of the distribution for Co-60 beams is significantly larger than that for high-energy X-ray beams. This indicates that the accuracy of calibration of high-energy X-ray beams is generally better compared to that for Co-60 beams. The fraction of large deviations (beyond 10%) is higher for Co-60 beams (8%, 19/242) than for high-energy X rays (4%, 10/228), an effect that is not inherent to the machine type (linear accelerator versus cobalt machine). This result might be explained by the fact that the centers with linear accelerators are supported by better medical physics services, whereas the institutions with only Co-60 units do not always have access to well-qualified medical physicists and to dosimetry equipment. Indeed, the results for Co-60 beams in the centers that have both linear accelerators and Co-60 units are similar to the results for centers that only have linear accelerator beams.

When comparing the results of the TLD audits for 2000–2003 for Co-60 beams in different world regions, Latin America and the Caribbean had a noticeably higher fraction of acceptable results (87%, or 210/242) than did other regions (78%, or 463/595). There was a similar pattern for deviations beyond the 5% level, with it being only 13% (32/242) in Latin America and the Caribbean, compared to 22% (132/595) in other regions. Poor results are related to obsolete, malfunctioning Co-60 units and unreliable or out-of-date dosimetry systems used by medical physicists for Co-60 beam calibrations. In Latin America and the Caribbean the dosimetry equipment age and quality do not constitute a large-scale problem (see the subsection below entitled "Status of dosimetry equipment"). In addition, the age of the Co-60 units in Latin America and the Caribbean, as reported on the TLD data sheets for 2000–2003, was quite balanced, with 60% of the machines being more than 10 years old and 40% being newer than that. Of the Co-60 units, 20% of them had been installed after the year 2000, and 25% were more than 20 years old. In a few cases, poor maintenance led to malfunctions in the radiotherapy machines, producing major TLD discrepancies.

The situation is quite different for the results of the IAEA/WHO TLD audits for high-energy X-ray beams from linear accelerators. Discrepancies in dosimetry occurred more frequently in Latin America and the Caribbean than in the other geographical regions (Table 2). In other regions the institutions operating linear accelerators are typically staffed with well-trained medical physicists and are equipped with the relevant dosimetry systems, which is not the case in some hospitals of Latin America and the Caribbean. Unfortunately, some linear accelerator-based facilities in Latin America and the Caribbean are operated without the appropriate medical physics support (see the subsection entitled "Availability of medical physics staff in radiotherapy centers"), which typically leads to poorer TLD results and may constitute a potential risk of errors in the dose delivered to patients treated at these facilities. Also, approximately 20% of linear accelerators in Latin America and the Caribbean are older than 20 years, and, if not properly maintained, they may not be as reliable as new machines.

FIGURE 2. Percentage of the results of the IAEA/WHO thermoluminescent dosimetry (TLD) audits within the 5% acceptance limit for radiotherapy centers in Latin America and the Caribbean[a]



[a] The light gray area indicates results obtained in the first check, and the dark gray area corresponds to the percentage of results that were improved in the follow-up process and that achieved the 5% acceptance level. The smooth lines refer to average values.

IMPROVEMENT OF THE TLD RESULTS IN LATIN AMERICA AND THE CARIBBEAN

There was a systematic rise in the fraction of TLD results within the acceptance limit of 5% in Latin America and the Caribbean between 1990 and 2003 (Figure 2). Although less pronounced, a similar rise occurred in other world regions over the same period. The improvement in Latin America and the Caribbean was considerable, with an increase in acceptable results from approximately 55% in 1990 to 90% in 2003. This is mainly due to greater interest in quality assurance in radiotherapy and the regular participation of centers in the TLD audit program. The rate of increase in the percentage of beams within the acceptance limit is expected to be slower in the future, as more institutions with limited resources (having no medical physicists or dosimetry equipment) join the TLD program. To bring the new participants to the level of well-performing centers, an increased allocation of resources for equipment and for training of medical physicists would be required. Since 1996 all hospitals worldwide participating in the IAEA/WHO program that have had poor TLD results have been contacted by IAEA/WHO to identify and resolve the problems in dosimetry and have been offered a second, follow-up TLD check. In instances where deviations are not corrected during the follow-up process, the next step involves support to the local medical physicists by experts in medical radiation physics, either recruited nationally or, in cases where such expertise does not exist in the country, recruited internationally. In Latin America and the Caribbean the follow-up procedures are managed by PAHO, with the help of the national TLD coordinators. In isolated cases in Latin America and the Caribbean, the IAEA directly contacted centers to assist in the resolution of the discrepancies. A few persistent deviations required the assistance of IAEA experts, who analyzed the reasons for the discrepancies during on-site visits and assisted local staff in implementing corrective actions.

Thanks to these actions by the IAEA, PAHO, and local experts, several participants in Latin America and the Caribbean improved their results in the follow-up TLD irradiation, which resulted in an increase in the fraction of acceptable TLD results for the beam calibration to approximately 95% in 1996–2003. This 95% included the correct results that did not require being followed up as well as the poor results corrected in the follow-up process. Unfortunately, 5% of the results remained uncorrected, either due to a failure to respond to the IAEA and PAHO efforts or due to local problems that could not be resolved without the allocation of additional resources.

REASONS FOR THERMOLUMINESCENT DOSIMETRY RESULTS OUTSIDE THE ACCEPTANCE LIMIT

For all data sheets, the IAEA verifies the participant's calculation of the dose delivered to the TLD based on the data reported. Any discrepancy between the dose calculated by a participant and the dose calculated by the IAEA is investigated. However, special attention is given to data sheets where discrepancies between the participant's stated dose and the dose determined with the TLD occur.

Three of the most common errors that occurred in all the geographical regions in 2000–2003 pertained to: (1) the confusion of the clinical geometry setup for TLD irradiation; (2) incorrect calculation of the irradiation time for the wrong depth, even though the TLD was placed at the prescribed depth; and (3) errors related to the combination of various mistakes in the dose calculation. More than half the deviations had reasons that could not be traced because of a lack of dosimetry data or because of an inconsistency in the data that were reported. When either the information related to the clinical output of the audited radiotherapy machine or the details of dose measurement are missing, it is not possible to provide an explanation of the deviation detected between the dose reported by the institution and the dose measured by the TLD. Some problems are caused by improper use of dosimetry equipment or poor treatment-machine conditions. Other problems are due to insufficient training of staff working in radiotherapy.

The frequencies of deviations outside the acceptance limit in Latin America and the Caribbean due to TLD setup errors were similar to those observed in other world regions during 2000–2003. However, several typical errors registered in other regions did not occur in the TLD audits in Latin America and the Caribbean. These errors occurring only in the other regions included some that were caused by incorrect use of old, exposure-based dosimetry codes of practice, misunderstanding of calibration coefficients, and incorrect use of plastic-to-water dose conversion factors for the measurements made in plastic phantoms. (Although they are not recommended by the modern dosimetry codes of practice, plastic phantoms are occasionally used for beam calibrations in centers not having the proper water phantoms.) The radiotherapy beam calibration is usually performed by medical physicists in a water phantom, and the dose calculation follows up-to-date dosimetry codes of practice that are based on air kerma calibrations or on absorbed dose to water calibrations. As noted in a subsequent subsection entitled "Use of dosimetry codes of practice for dose determination," in general, old, exposure-based dosimetry protocols are not used anymore in Latin America and the Caribbean. However, in Latin America and the Caribbean the percentage of "unknown reasons" for poor TLD results is significantly higher compared to that in other world regions, due to the large number of data sheets in Latin America and the Caribbean submitted without dosimetry data.

In several instances that took place in 1969–2003 in various parts of the world, large TLD deviations confirmed clinical observations of inadequate dosimetry practices in centers, or the deviations even uncovered accidents in radiotherapy. In an overexposure of patients in Costa Rica in 1996, more than 100 patients were given, in a one-month period, almost twice the prescribed dose (10). This resulted in the death of 42 patients within 9 months of the accident and in serious injuries to many others. In another hospital the ratios of D_{TLD}/D_{stat} varied from 0.61 to 1.20 in subsequent TLD audits, due to erratic functioning of the Co-60 shutter system, which was attributable to poor maintenance of the Co-60 unit. No output measurements had been made for a few years, and several patients treated with this Co-60 beam might have been affected. A patient underdosage that leads to a decrease in the local tumor control rate and thereby jeopardizes the success of radiotherapy treatment may not be detected by clinical observation for several years (11). If beam output measurements are not performed regularly, the TLD audit becomes a useful tool to recognize and correct the problem before clinical results are affected.

Nevertheless, poor TLD results do not always reflect errors in the beam output routinely used to treat patients in clinics. Even if TLDs indicate doses that are not consistent with the reported doses, the doses routinely given to patients might still be correct. Typically, this occurs where the TLD dose was calculated and reported in the data sheet for the specified geometry setup but, by mistake, the actual TLD irradiation was conducted using another geometry. The differences in geometry result in discrepancies between the reported dose and the TLD-measured dose. Mishaps during the TLD irradiation are not relevant to routine clinical procedures if quality control procedures for clinical dosimetry are well established and ensure that the beam data are properly implemented in the clinical routine. Problems with TLD irradiations pertain especially to the circumstances where junior physics or medical staff are given the special task of TLD irradiation without their fully understanding the instructions. A few extreme deviations that were caused by communication problems have been observed. For example, in one case, TLDs were irradiated twice, resulting in the ratio of D_{TLD}/D_{stat} being close to 2. In another center, TLDs were irradiated with 2-Gy fractions for four days in a row, resulting in the ratio of D_{TLD}/D_{stat} being close to 4. (This result is not included in the TLD statistics reported in this report.) Fortunately, these cases had no direct clinical relevance.

DOSIMETRY INFORMATION FROM THE TLD DATA SHEETS IN 2000–2003

Of the 470 data sheets submitted by the participants of the IAEA/WHO TLD dosimetry audits in Latin America and the Caribbean in 2000–2003, the information on procedures for dose determination from ionization chamber measurements was given for only 310 of them (66%); that is, 160 data sheets were submitted without reporting data related to the beam calibration. In contrast, in other world regions, approximately 80% of the participants in the TLD audit program reported at least some dosimetry data.

Availability of medical physics staff in radiotherapy centers

The participating institutions are requested to indicate in their data sheets whether the TLD irradiation was performed by a medical physicist or by medical personnel (either a radiation oncologist or a radiotherapy technologist). With the audits in Latin America and the Caribbean in 2000–2003, the availability of a medical physicist responsible for dosimetry was confirmed in 391 of the 470 cases (83%), including 8 in which the services of a visiting physicist were used. On 79 of the 470 data sheets (17%), the centers reported no medical physicist on staff, so no beam calibration details were provided. These 79 cases were part of the 160 data sheets that were submitted without providing information on ion chamber measurements. The remaining 81 of the 470 data sheets (17%) without measurement information most likely indicate that the local medical physicist could not perform measurements due to the lack of dosimetry equipment.

Table 3 shows the distribution of the results (in terms of D_{TLD}/D_{stat}) for the centers in Latin America and the Caribbean in 2000–2003 that had a medical physicist on duty for regularly treating patients and for the centers that did not have a physicist on duty. The spread of the TLD results is smaller (standard deviation of 0.070) for institutions with medical physicists on duty than for those without such staff (standard deviation, 0.134). In addition, 89% (345/391) of the centers with medical physicists had TLD results within the acceptance limit, whereas only 70% (55/79) of the centers without a medical physicist performed successfully in this TLD audit. This compares with the worldwide average of 86% (Table 1).

TABLE 3. Results of the IAEA/WHO thermoluminescent dosimetry (TLD) audits in 2000–2003 for Latin America and the Caribbean, performed with and without medical physics support for treating patients on a regular basis, for 242 Co-60 beams and 228 high-energy X-ray beams from linear accelerators

Parameter	Medical physicist on duty	No medical physicist on duty
Number of audits	391	79
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$ [a]	1.011	0.989
Standard deviation	0.070	0.134
Percentage of acceptable results[b]	89%	70%

[a] $\frac{D_{TLD}}{D_{stat}}$ is the mean of the distribution of the TLD results expressed as ratios of the IAEA-determined dose (D_{TLD}) relative to the dose stated by the center (D_{stat}).

[b] The "acceptable" TLD results were those that were within a 5% limit of the TLD-measured to center-stated dose, i.e., $0.95 \le D_{TLD}/D_{stat} \le 1.05$.

Although not shown in Table 3, there are a large number of radiotherapy centers running medical accelerators in Latin America and the Caribbean without the regular support of a medical physicist. For example, in some hospitals a visiting physicist performed the calibration of linear accelerator beams several months before the date of the TLD irradiation. Such sporadic or infrequent beam calibrations are considered inadequate. The output of radiotherapy beams should be checked on a regular basis. Both the American Association of Physicists in Medicine (AAPM) (12) and the IAEA (13) strongly recommend that radiotherapy centers implement QA programs and employ a full-time medical physicist, especially if they operate linear accelerators. Using the services of visiting physicists may be necessary in some cases due to the insufficient number of qualified medical physicists in Latin America and the Caribbean. However, the data in Table 3 show that hospitals providing radiotherapy services without medical physicists or dosimetry equipment had noticeably poorer results, which may have had a negative impact on the accuracy of the dose delivered and on patient outcomes.

Status of dosimetry equipment

As mentioned earlier, at least partial information on dosimetry equipment and procedures was given on 66% (310/470) of the data sheets obtained from Latin America and the Caribbean in 2000–

2003. The sheets indicated that the most commonly used dosimetry equipment, referred to as modern, 0.6 cm^3 Farmer-type chambers, was from well-known manufacturers such as Nuclear Enterprises or Physikalisch-Technische Werkstätten (PTW). Sometimes small waterproof chambers of 0.1–0.3 cm^3 were used for beam calibration, but they are not generally recommended by modern dosimetry codes of practice for calibrating radiotherapy beams. There are practically no users of old or atypical dosimetry equipment in Latin America and the Caribbean, whereas in other regions about 10% of the centers use obsolete or locally-made ionization chambers and electrometers. Most chambers in Latin America and the Caribbean have valid calibration certificates from SSDLs or manufacturers, with the percentage reporting calibration coefficients in terms of absorbed dose to water ($N_{D,w}$), air kerma (N_K), and exposure (N_X) being approximately 18%, 60%, and 22%, respectively.

Use of dosimetry codes of practice for dose determination

Using the data sheets from the audits carried out in Latin America and the Caribbean in 2000–2003, the physicists also provided information on the dosimetry code of practice used for dose determination, including numerical values of the correction factors and interaction coefficients applied for the calculation of absorbed dose to water from ionization chamber measurements. Table 4 shows the results (in terms of D_{TLD}/D_{stat}) for the centers using different dosimetry protocols. The results based on modern $N_{D,w}$ protocols showed a smaller standard deviation (0.021) than did the results based on N_K protocols (0.038). The groups based on old N_X protocols or "unknown" protocols had a standard deviation (0.036) that was similar to the one for the N_K protocols. These standard deviations are consistent with the results from other world regions. The use of old N_X-based protocols has practically ceased in Latin America and the Caribbean (Table 4). In comparison, approximately 10%–15% of the participants of the TLD dose quality audit in other world regions report the use of N_X-based protocols.

Table 4 shows that the air kerma-based codes of practice (IAEA TRS-277 (14) and AAPM TG-21 (15)) were the main dosimetry protocols used for radiotherapy beam calibration in Latin America and the Caribbean as of 2000–2003. The use of recently-developed absorbed dose to water-based codes of practice (IAEA TRS-398 (9) and AAPM TG-51 (16)) was limited but growing. Previous research (4) has shown that despite the differences in protocols, traceability to different laboratories, and variations in dosimetry equipment used worldwide, there is a good agreement in the determination of absorbed dose to water for photon beams when the different dosimetry protocols are used correctly. The TLD results in Latin America and the Caribbean shown in Table 4 support this conclusion.

SUMMARY AND CONCLUSIONS

Over a period of 34 years of operation, from 1969 through 2003, the IAEA/WHO TLD audits checked the calibration of approximately 5 200 photon beams in over 1 300 radiotherapy centers in 115 countries around the world. Of these beam audits, more than 1 850 of them were performed in Latin America and the Caribbean. For the 2000–2003 pe-

TABLE 4. Results of the IAEA/WHO thermoluminescent dosimetry (TLD) audits in 2000–2003 for Latin America and the Caribbean, grouped according to the dosimetry codes of practice used by the radiotherapy centers

	Dosimetry codes of practice		
Parameter	$N_{D,w}$-based[a]	N_K-based[b]	Old N_X-based or unknown[c]
Number of audits (percentage)	42 (14%)	245 (80%)	23 (6%)
Mean of the distribution, $\frac{D_{TLD}}{D_{stat}}$[d]	1.011	1.008	1.014
Standard deviation	0.021	0.038	0.036

[a] $N_{D,w}$ is ionization chamber calibration coefficient in terms of absorbed dose to water.
[b] N_K is ionization chamber calibration coefficient in terms of air kerma.
[c] N_X is ionization chamber calibration coefficient in terms of exposure.

[d] $\frac{D_{TLD}}{D_{stat}}$ is the mean of the distribution of the TLD results expressed as ratios of the IAEA-determined dose (D_{TLD}) relative to the dose stated by the center (D_{stat}).

riod, the fraction of acceptable results in all regions was higher than in previous periods, but with a more pronounced improvement in Latin America and the Caribbean than in the other regions.

The improvement in dosimetry performance in Latin America and the Caribbean has been considerable, with an increase in acceptable results from less than 60% before 1990 to about 95% in 2000–2003. This is mainly due to a greater interest in quality assurance in radiotherapy and to regular participation in the TLD audit program. For centers to reach and maintain an adequate level of dosimetry, it is important for them to regularly participate in external TLD audits. Compared to institutions that have participated in audits for a longer period of time, centers that participate in a TLD audit for the first time are less likely to achieve results within the 5% acceptance limit.

The TLD results for high-energy X rays from linear accelerators are generally better than those for Co-60 beams in all world regions. However, in Latin America and the Caribbean, discrepancies in X-ray beam calibrations occurred more frequently than in other geographical regions. This was especially true in centers where linear accelerator-based facilities were being operated without the appropriate medical physics support, which typically leads to poorer TLD results.

For the results outside the 5% acceptance limit, the IAEA has established a follow-up program, which increased the percentage of acceptable results to approximately 95% in 2000–2003 for the world overall. All centers with poor results are contacted, but some (5%) have not yet responded to efforts by the IAEA/WHO to help identify and resolve the problems.

In all world regions in 1969–2003, large deviations were observed in terms of over- and underdosage of TLDs. In several instances the overdosage confirmed clinical observations of inadequate dosimetry practices. On the other hand, a patient underdosage may not be detected by clinical observation for several years. Therefore, the TLD audit is a very useful tool for recognizing and correcting a problem before it becomes clinically evident.

In 2000–2003 the frequency of deviations outside the acceptance limit in Latin America and the Caribbean that was due to setup errors or to incorrect calculations of irradiation time was similar to the frequency found in the other world regions. However, typical errors registered in other regions, such as confusion in the use of old N_X-based dosimetry protocols and a misunderstanding of calibration coefficients, did not occur in the TLD audits in Latin America and the Caribbean. This is because old N_X-based protocols are now used less frequently, with centers in Latin America and the Caribbean switching to up-to-date N_K-based codes of practice and the recently-developed $N_{D,w}$-based codes of practice. In all world regions the institutions running radiotherapy services without qualified medical physicists and without dosimetry equipment attain poorer results than do the centers that are properly staffed and equipped. Lack of medical radiation physicists is a particularly serious problem in Latin American and Caribbean countries.

We can conclude that the unsatisfactory TLD results seen in past decades in Latin America and the Caribbean have improved considerably. Nevertheless, to achieve parity with the dose audit results for centers in the industrialized countries of North America and the European Union (5), further improvement will be needed. For this to occur, strengthening of the radiotherapy infrastructure in Latin America and the Caribbean will be required, both in terms of qualified medical radiation physics staff and appropriate dosimetry equipment.

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SINOPSIS

Auditorías de las dosis usadas en centros de radioterapia en América Latina y el Caribe: tendencias observadas en el período de 1969–2003

Desde 1969, el Organismo Internacional de Energía Atómica y la Organización Mundial de la Salud (junto con la Organización Panamericana de la Salud en países de América Latina y el Caribe) han puesto en marcha un programa de auditorías dosimétricas por correo que se basa en la dosimetría termoluminiscente (DTL) para servicios de radioterapia. El objetivo del programa es ofrecer una verificación dosimétrica independiente de la calibración de los haces de radiación que se usan para tratar a los enfermos de cáncer. La obtención de buenos resultados en radioterapia depende de una dosimetría exacta. Entre 1969 y 2003 se verificó la calibración de aproximadamente 5 200 haces de fotones en más de 1 300 centros de 115 países de todo el mundo. El 36% de esas auditorías se efectuaron en América Latina y el Caribe, donde a lo largo de los años se observó un mejoramiento de los resultados. Por des-

gracia, ha habido varios casos en servicios de radioterapia de varias partes del mundo en los que las grandes desviaciones de la DTL han confirmado las observaciones clínicas de prácticas dosimétricas inadecuadas e incluso de accidentes de radioterapia como el ocurrido en Costa Rica en 1996. Los hospitales o centros cuyos servicios de radioterapia funcionan sin contar con físicos médicos calificados o que carecen de equipo de dosimetría obtienen peores resultados que los dotados de personal y equipo adecuados. Cuando se obtienen malos resultados en las mediciones de DTL en un determinado centro, un programa de seguimiento puede ayudarlo a mejorar la dosimetría. No obstante, para lograr resultados de auditoría semejantes a los obtenidos por los centros de los países industrializados, es necesario seguir fortaleciendo la infraestructura de la radioterapia en América Latina y el Caribe.

Palabras clave: radioterapia, control de calidad, auditoría médica, cooperación internacional, países en desarrollo, América Latina, región del Caribe.

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