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TLD and OSLD dosimetry systems for remote audits of radiotherapy external beam calibration

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Abstract

The Imaging and Radiation Oncology Core QA Center in Houston (IROC-H) performs remote dosimetry audits of more than 20,000 megavoltage photon and electron beams each year. Both a thermoluminescent dosimeter (TLD-100) and optically stimulated luminescent dosimeter (OSLD; nanoDot) system are commissioned for this task, with the OSLD system being predominant due to the more time-efficient read-out process. The measurement apparatus includes 3 TLD or 2 OSLD in an acrylic mini-phantom, which are irradiated by the institution under reference geometry. Dosimetry systems are calibrated based on the signal-to-dose conversion established with reference dosimeters irradiated in a Co-60 beam, using a reference dose of 300 cGy for TLD and 100 cGy for OSLD. The uncertainty in the dose determination is 1.3% for TLD and 1.6% for OSLD at the one sigma level. This accuracy allows for a tolerance of $\pm 5\%$ to be used.

Keywords

TLD; OSLD; remote audit; output verification

Introduction

The IROC-H QA Center is an organization dedicated to providing radiation oncology quality audit programs in support of the National Cancer Institute's clinical trials. These programs help to ensure high quality data, thereby maximizing clinical trial power and improving clinical outcomes for cancer patients worldwide. One of the initial requirements for an institution wishing to participate in clinical trials is the verification of the reference output of the beams used for radiotherapy treatment. This program began at the Radiological Physics Center (RPC) (then named IROC-H) in 1968. This program has continually grown over the decades, and during 2015, the office monitored more than 2100 institutions and verified the output of more than 22600 beams, making this by far the largest program of its size in the

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world. The remote dosimetry audit program is established based on detectors that can be mailed, are able to be irradiated in a simple geometry, retain the dosimeter signal after irradiation in a predictable manner, and can be read-out in a reproducible way. Both TLD and OSLD are commissioned to determine doses for photon and electrons beams with energies within the radiotherapy range. The TLD program has been in use for decades, and was previously introduced by Kriby et al (1999); a similar program operated by the IAEA has also been described (Izewska 2003). The OSLD system operated by IROC-H now predominate use because it has a much shorter read-out process, improving throughput. However, the IROC-H OSLD dosimetry system has not been previously presented, particularly in comparison to the more familiar TLD programs. This work presents this information.

Material and Methods

IROC-Houston's TLD system is based on TLD-100 (LiF:Mg,Ti) powder packaged into cylindrical Teflon capsules filled with 20 to 22 mg of crystal (Figure 1). The reading is defined as the charge collected from the reader per mass of powder. The reading is done with one of several Harshaw Model 3500 readers (Thermo Scientific, Waltham MA) with a 2 min read cycle. The mass is measured with a digital balance. After use, the TLD powder is collected and, as a large volume of powder, annealed and recommissioned as a new batch. The annealing process is done by the manufacturer.

IROC-Houston's OSLD system is based on nanoDot dosimeters (Landauer Inc., Glenwood Il). The reading for this system is defined by the number of counts from the Landauer MicroStar InLight reader (Figure 1) with three successive 7-second readings of each dosimeter. After use, the OSLD are optically bleached and re-used repeatedly up to a total cumulative dose of 10 Gy (beyond which the detector sensitivity begins to change dramatically (Omatoyo 2011, Jursinic 2007, Reft 2009). The bleaching process is done in-house using a custom made light box.

For any institution participating in NCI-sponsored clinical trials, each clinically active photon beam is monitored every year with an IROC-H remote audit. Each clinically active electron beam is monitored on a 2-year cycle, with half of the electron beams monitored on successive years. Results for standard C-arm linear accelerators are presented in this work. For each beam being monitored at an institution, a separate acrylic mini-phantom loaded with dosimeters is mailed (Figure 2). The dimension of the blocks are the same for TLD as for OSLD detectors and ranged from $3\text{ cm} \times 4.5\text{ cm} \times 1.5\text{ cm}$ deep to $6.5\text{ cm} \times 6.5\text{ cm} \times 5.5\text{ cm}$ deep for photon beams (where smaller mini-phantoms are used for lower energy photon beams) and 8.5cm cube for electron beams. The dimensions of the miniphantoms are based on the type of beam and the energy. For electron beams the dimensions are enough to provide full phantom scatter to the location of the detector. In the case of photon beams, the dimensions are sufficient to provide electronic scatter equilibrium, but do not provide full photon scatter equilibrium. The use of mini-phantoms for the photon beams reduces the cost of shipping these blocks, but then requires the application of a backscatter correction factor to determine output in a full phantom condition. For TLD, the phantom is loaded with 3 dosimeter capsules; for OSLD, the phantom is loaded with 2 nanoDots. This number of

dosimeters occupies approximately the same space in the miniphantom, allowing for the same outer phantom geometry between both systems.

The geometry for irradiation is similar to reference conditions defined by dosimetry protocols. For photon beams, the mini-phantom is placed on a platform (included in the shipping and shown in Figure 2), which is located at 100 cm from the source with the miniphantom located on top of the platform in the center of a 10 cm × 10 cm field. For electron beam, the top of the phantom is set at 100 cm from the source. Any differences between this irradiation geometry and the linac calibration geometry are accounted for by IROC-H with appropriate geometric and TMR corrections. The dose level delivered is 300cGy for TLD and 100cGy for OSLD. The dose to the OSLD is lower to increase the number of uses of each detector before 10 Gy of cumulative dose is delivered and the dosimeter is no longer usable.

Both the TLD and OSLD systems are intended to be used under very strict irradiation and read-out conditions. However, to allow for variations from this procedure, the dosimetry systems are broadly characterized for each batch. Beam quality dependence (k_Q) is characterized for energies ranging from Co-60 to 23 MV (x-rays) and 6 to 23 MeV (electrons). Non-linearity effects (k_L) are characterized between 25 cGy and 3.5 Gy (OSLD) or 6 Gy (TLD). Fading effects (k_F) are characterized from 1 day after irradiation to 6 months after irradiation. These characterizations are conducted during the commissioning of a new batch of dosimeters.

The dose to the detector from relatively arbitrary irradiation conditions can therefore be determined using the general formalism:

$$D = \overline{M}_{raw} \times k_{s,i} \times N_{D,W} \times k_Q \times k_L \times k_F \quad (1)$$

Where $\overline{M}_{raw}$ is the raw signal (signal per mass (TLD) or counts (OSLD)), averaged across the 3 TLD or 2 OSLD. The correction: $k_{s,i}$ corrects for the individual variation in sensitivity between different dosimeters of the same batch. Because IROC-H's TLD program is based on powder, the sensitivity is uniform and no $k_{s,i}$ correction is necessary.

$N_{D,W}$ is the calibration coefficient that relates signal to dose. This coefficient is determined for each dosimeter reading session by the irradiation and read-out of reference dosimeters. These reference dosimeters are calibration dosimeters irradiated under controlled conditions to a known dose in a Co-60 beam.

The total uncertainty (standard error) of the determined dose from 3 TLD was previously reported as 1.3% (Kirby 1999). The total uncertainty (standard error) of the determined dose from 2 OSLD was calculated in this work based on uncertainty of each of the components of the equation 1, applying equation 2 recursively:

$$var(XY) = var(X)var(Y) + var(X)E(Y)^2 + var(Y)E(X)^2 \quad (2)$$

where X and Y are the variables: M_{raw} , $k_{s,i}$, $N_{D,w}$, k_L , k_F , and k_Q , which all have underlying uncertainties. This method does not rely on the normality assumption of the distribution, or on any type of mathematical approximation. Standard deviations for all the factors were experimentally estimated, so uncertainties, for example in the raw readings, will depend on the specific reading process, and even reader and operator.

Results

The correction factors that have been determined through batch commissioning are discussed below:

Values for k_L (from 25 to 600cGy for TLD normalized to 300 cGy, and from 25 to 350 cGy for OSLD normalized to 100 cGy) ranged from 1.065 to 0.891 for TLD and 1.019 to 0.933 for OSLD. Linearity is a substantial correction for both dosimetry systems.

Values for k_F ranged between 1.040 (1 day post irradiation) to 0.965 (180 days post irradiation) for TLD (normalized to 2 weeks) and 1.015 (1 day) to 0.968 (180 days) for OSLD (normalized to 2 days). A shorter wait time was used for OSLD (fading time was normalized to 2 days instead of 2 weeks) for two reasons. First, fading is less pronounced for OSLD, so less uncertainty is introduced when readings are done closer in time to the irradiation. Second, the OSLD time was established in 2010, decades after the TLD time was established, and expected time to read the dosimeter had shortened because of improved workflow.

The values for the beam quality correction k_Q ranged between 1.000 to 1.051 for TLD and 1.012 to 1.053 for OSLD for 4 to 23 MV photons/MeV electrons relative to Co-60. Of particular note, this correction factor in this framework also includes the backscatter term for the mini-phantom. That is, this correction factor relates signal in Co-60 in a Co-60 mini-phantom to the signal in a higher energy beam in a corresponding mini-phantom. The actual beam quality dependence of TLD-100 and nanoDots has been previously shown to be about 2% between Co-60 and higher energy x-ray or electron beams. (Jursinic 2007; Reft 2009; Dunn *et al.* 2013)

Historically, the variation of these correction factors between batches was found to be less than 1% for fading, up to 3% for dose linearity and less than 2% for energy for both systems. All of these corrections have been found to be reader independent.

As implemented into a remote audit, the results of more than 20,000 beam output checks with TLD and OSLD are shown in Figure 3. This mailed program reports the ratio of the dose detected to the dose reported by the institution. The average output was $1.000 \pm 1.9\%$ for TLD and $0.999 \pm 1.7\%$ for OSLD. The ratio averages were also analyzed per beam modality and per energy and showed no differences. Of the ~20,000 measurements, 2.4% were outside the 5% tolerance established by IROC-Houston, prompting follow-up action.

The uncertainty in the reported dose from the IROC Houston TLD program was previously calculated to be 1.3% (Kriby 1999). This value is less than the 1.9% measured standard deviation shown in Figure 3. This difference is reasonable because the calculated value is the

theoretical uncertainty in the dosimeter, whereas the measured value includes variation as a result of errors in the calibration of institutional beams, as well as errors in irradiating the TLD (both introducing noise into the measured distribution of doses).

For the OSLD program, our analysis found the uncertainty in the reported dose from this dosimetry system was 1.7% at one sigma level, which is slightly larger than the 1.3% found for TLD. This difference is in large part because only 2 dosimeters are used instead of 3 for TLD. This calculated uncertainty is identical to the observed standard deviation in the OSLD results from multiple experimental readings (Figure 3), which was also 1.7%. It is unclear why the calculated and measured standard deviations agree, when in reality the measured distribution should be larger because of the added spread from calibration and irradiation errors. Consequently, the 1.7% uncertainty calculated can be viewed as a conservative estimate of the achievable accuracy of this dosimetric system. Of additional note, the calculated uncertainty of 1.7% corresponds to irradiations done under conditions close to the reference conditions (i.e., close to 1 Gy and close to 2 days post irradiation). If irradiations are done under more different conditions (e.g., 3.5 Gy and 180 days post irradiation) the magnitude of the applied correction factors increases, and correspondingly, the uncertainty in the corrections increases. Fortunately, in our analysis, when the correction factors were allowed to vary to the extremes of our commissioned ranges, the maximum uncertainty increased to only 1.8%. This result leaves us confident in continuing to apply the $\pm 5\%$ tolerance window on this output audit, regardless of whether it is conducted with TLD or OSLD.

Conclusions

Numerous batches of TLD and OSLD have been commissioned and used for remote audits by IROC-Houston. These dosimeters have proven to be robust and well-suited for remote audits of beam output. OSLD have been found to provide benefit in terms of read-out time, which expedites the reading of thousands of dosimeters. Offsetting this benefit is the finite life-span of this dosimeter (10 Gy) which requires that each dosimeter's cumulative dose history be tracked, and the different sensitivity of each dosimeter, necessitating the determination of the element sensitivity correction ($k_{s,i}$) for each.

For more than 16000 TLD results and more than 4200 OSLD results, the average ratio for TLD at the point of dose verification is $1.000 \pm 1.9\%$ for TLD and $0.999 \pm 1.7\%$ for OSLD. These results indicate the equivalence in terms of accuracy of the TLD and OSLD programs.

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Highlights

Remote dosimetry audits of radiotherapy megavoltage photon and electron beams using both a thermoluminescent dosimeter (TLD-100) and optically stimulated luminescent dosimeter (OSLD; nanoDot) system.

The TLD and OSLD systems are intended to be used under very strict irradiation and read-out conditions.

The uncertainty in the dose determination is 1.3% for TLD and 1.6% for OSLD at the one sigma level. This accuracy allows for a tolerance of $\pm 5\%$ to be used for output check.

Fig. 1.
TLD and OSLD system (detectors and readers)

Fig. 2.
Acrylic block housing dosimeters (left). Geometry used for irradiation of the acrylic block (right)

Fig. 3.
Histogram of results of mailed output check verification done with TLD and OSLD.