TLD dose measurement: A simplified accurate technique for the dose range from 0.5 cGy to 1000 cGy

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A simplified TLD technique characterized by high precision and reproducibility of dose measurement is presented. One hundred eighty LiF TLD rods 1 mm diam $\times$3 mm length as obtained from the manufacturer were annealed for 1 h at 400 °C followed immediately by 2 h at 105 °C. After exposure to a dose of 1 Gy of 4 MV x rays, TLDs were annealed for 15 min at 105 °C, then read out. TLDs were then sorted into five groups, ranging from 26 to 50 rods each with approximately equal sensitivity after correcting for the drift in the sensitivity of the TLD reader during the readout session. Maintaining group identity, the TLDs were again annealed, irradiated and read out. Fewer than 10% of the TLDs were removed from each group because the corrected readings differed from the respective group mean by more than 3.5%. The standard deviation of the readout was approximately 1.5% within each group. The planchet heater was not flushed with nitrogen gas. Various tests were performed to assess the stability of the group sorting technique and the linearity of TLD dose response. After reannealing, five TLDs were randomly drawn from one of the presorted groups, and subjected to various dose of 4 MV radiation over the range from 0.5 to 1000 cGy. This resulted in an average readout standard deviation of 1.2%. Response per unit dose was almost flat over the range from 0.5 cGy to 100 cGy, and increased by 15% over the range from 100 cGy to 1000 cGy. TLD sensitivity was affected by the duration of the anneal, but was virtually independent of the various time delays between irradiation, prereadout anneal, and readout. The group annealing and sorting (GAS) procedure provides a simple, reliable, precise, convenient, and accurate method for TLD measurements.
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I. INTRODUCTION

Thermoluminescent dosimetry (TLD) is used in radiation therapy for dose measurements in total skin irradiation,[1,2] total body irradiation,[3,4] brachytherapy,[5–11] stray radiation,[12–15] and verification of dose delivery.[16,17] In these applications, TLDs are used to confirm or determine radiation dose in complicated geometries, to estimate the dose delivered to critical organs or to monitor special treatments such as total body irradiation. TLDs are used for dose measurement in small fields, for example, in radiosurgery and also used in a mailed TLD system for monitoring calibration of clinical photon and electron beams.[18] One of the most widely used TLD phosphors is TLD-100 (LiF), developed by the Harshaw Chemical Company in collaboration with Cameron.[19] TLDs of LiF in its purest form exhibit relatively little thermoluminescence which is the phenomenon of photon emission subsequent to heating. The presence of impurities, i.e., magnesium and titanium in TLD-100 LiF, appears to be necessary for radiation-induced thermoluminescence. When a crystalline TLD is irradiated, a minute fraction of the absorbed energy is stored in the crystal lattice. The energy stored in the irradiated TLD is recovered as visible light by placing it on a planchet heater in a commercially available TLD reader and heating the TLD in a light-tight chamber. A photomultiplier tube (PMT) placed in the TLD reader detects the light emitted from the TLDs.

Characteristics of TLD that are particularly important for radiation dosimetry include variability of the TL response vs readout temperature, referred to as the glow curve, the variability of TL response related to annealing procedures and nonlinearity of the TL dose response. Zimmerman *et al.*[20] found that several prominent peaks in the TLD-100 glow curve decay at room temperature with an approximate half-life of 5 min (peak 1), 10 h (peak 2), 0.5 year (peak 3), 7 years (peak 4), and 80 years (peak 5). The peaks with longer half-life are the most stable, and potentially the most suitable for radiation dosimetry. The peaks with shorter half-life are undesirable signals, which can be removed by various techniques of pre- and postirradiation annealing. As shown by Zimmerman *et al.*,[20] the standard annealing procedure of 80 °C for 24 h, referred to as the low temperature annealing, almost eliminates the first two short half-life peaks entirely, and lessens the influence of the third peak. Buch discovered the effect of the low temperature annealing when he left a sample of LiF on top of a hot oven overnight.[21] Cameron *et al.*[22] and Zimmerman *et al.*[20] have proposed a standard preirradiation annealing procedure. The procedure consists of 400 °C for 1 h (high temperature annealing) to de-excite all traps in the phosphor, followed by 80 °C for 24 h (low temperature annealing) to redistribute traps to the desired single peak glow curve. An additional postirradiation annealing technique has been suggested by Booth *et al.*[23] In this procedure, TLDs were annealed for 1 h at 400 °C before irradiation and then for 10–15 min at 100 °C after irradiation and before readout. The latter part of the annealing procedure in this technique serves a similar purpose to the low temperature annealing in the preirradiation annealing procedure.

The presence of the nitrogen gas in the planchet chamber has been observed to affect the precision of TLD reading, especially for radiation doses below 10 cGy. Meigooni *et al.*[24] found that for radiation doses below 5 cGy, there was a large standard deviation in TL response, almost 100% of the signal, when TLDs were read without nitrogen gas flow in the TLD reader, whereas the standard deviation dropped to 5% with nitrogen gas flow. Other techniques have been proposed to improve the precision and stability of TLD dose measurements.[24–32] For example, TLDs may be individually identified and assigned relative sensitivity factors.[24]

We report here a simplified TLD technique characterized by high precision and reproducibility of radiation dose measurement. In this technique, TLDs are group-annealed, sorted, and subjected to prereadout annealing according to a procedure described in Materials and Methods. We also report data on the characteristics of TLDs when following this technique, in particular, linearity of radiation dose response, TL sensitivity, and TL signal fading.

II. MATERIALS AND METHODS

A. TLD irradiation

Lithium fluoride thermoluminescent dosimetry rods (TLD-100, Harshaw/Bicron, Solon, OH), 1 mm in diam, 3 mm in length, were used in this study. A single batch of 180 TLD rods purchased from the manufacturer were sorted into subgroups of equal sensitivity to radiation dose according to the protocol described below (Sec. II C). The radiation source was a 4 MV x-ray beam from a medical linear accelerator (Clinac 4/100, Varian Associates, Palo Alto, CA). The accelerator was calibrated according to the AAPM Task Group 21 protocol[33] with an output of 1.00 cGy/monitor unit at a depth of maximum dose for a water phantom in a $10 \times 10\,\mathrm{cm}^2$ field at a source to phantom surface distance of 100 cm. A polystyrene phantom was also used for all TLD irradiations. The phantom consisted of a stack of six square 25×25 cm slabs, each about 2.5 cm in thickness except for a top slab of 1 cm thickness used to place the rods at the depth of maximum dose in the phantom. The first 2.5 cm thick slab of polystyrene was machined with a special pattern of slots 1.5 mm deep to hold the TLDs for irradiation. The slots were aligned in a centered, symmetrical array at 7.62 mm intervals parallel to their long axes, and at 2.54 mm intervals in a direction perpendicular to the long axes, as described by Luxton *et al.*[34] Each irradiation was carried out in a $10 \times 10\,\mathrm{cm}^2$ field at a source to phantom surface distance of 100 cm. During setup for irradiation, the phantom with TLDs was carefully placed such that no TLD would lie in the shadow of the metal cross-hair of the accelerator head to avoid small dose variation caused by the wire. A maximum of six TLD rods were placed in each quadrant, for a maximum overall number of 24 TLDs during an individual irradiation. The TLD signal was read using a commercial TLD reader system (model 3000A, Harshaw, Solon, OH). TLD rods placed singly on the planchet were heated to 250 °C in 50 s.

For each TL measurement, background subtraction was performed. Background was defined as the average reading from a TLD rod not exposed to radiation. For each session of TLD exposure to radiation, up to 5 rods from the same group with about the same sensitivity as those used for measurement were set aside without any radiation. This baseline group then went through the same prereadout and readout procedure as the irradiated TLDs. The baseline readings were about 0.8 nC with PMT bias of 850 V. Care was taken to avoid any handling of the rods other than with clean stainless steel forceps.

B. Annealing procedures

The annealing procedures consisted of three steps; high temperature and low temperature annealing prior to irradiation and prereadout annealing at low temperature after irradiation. High temperature annealing was accomplished using a furnace preheated to 400 °C (Thermolyne Model No. F47925-70, Barnstead/Thermolyne, Dubuque, Iowa). The automatic temperature control provided a stable temperature to within ±1 °C. TLD rods, in a Pyrex beaker, were kept inside the furnace for 1 h. At the end of 1 h annealing at 400 °C, TLDs were immediately removed from the high temperature furnace and transferred into a low temperature furnace (Blue M, Model OV-12A, Blue Island, IL) where they remained for 2 h. The low temperature furnace had been preheated to 105 °C. For both high and low temperature annealing, the beaker with TLDs was carefully placed at the center of the furnace to avoid any unnecessary heat gradients that might increase variation in TLD response. After low temperature annealing, TLDs were removed from the furnace and cooled to room temperature. After being subjected to irradiation and prior to being read out, the TLDs were placed in a beaker or on a glass dish and were annealed for 15 min inside the low temperature furnace that had been preheated to 105 °C. In what follows, this procedure of 400 °C for 1 h, 105 °C for 2 h, and 105 °C prereadout for 15 min shall be referred to as the standard annealing procedure.

C. Sorting procedures

The batch of 180 TLDs as obtained from the manufacturer was initially annealed according to the procedure described above, i.e., 1 h at 400 °C followed immediately by 2 h at 105 °C. After exposure to a dose of 1 Gy of 4 MV x rays, the TLD rods were annealed for 15 min at 105 °C, then read out. The readout session was carried out in an uninterrupted manner, over a period of 4 h. After readout, each TLD rod was kept in an assigned bin with identification number for sorting purposes. The TLD reader system response to a

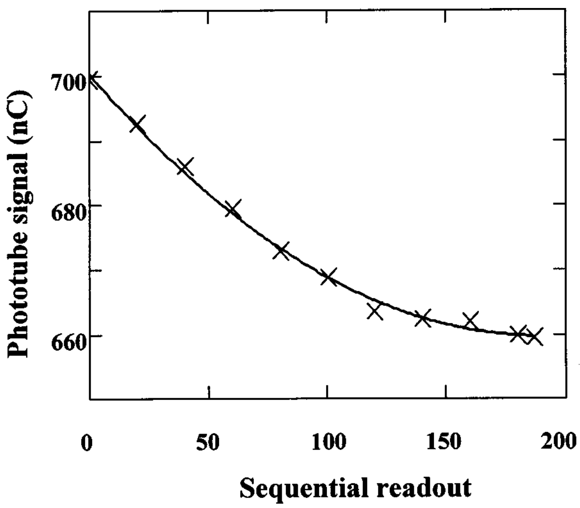

FIG. 1. The photomultiplier tube response to the built-in light source as a function of the number of the sequential readouts. The cross signs are the actual light source readings. The solid line is a fitting from a model of a nonlinear function.

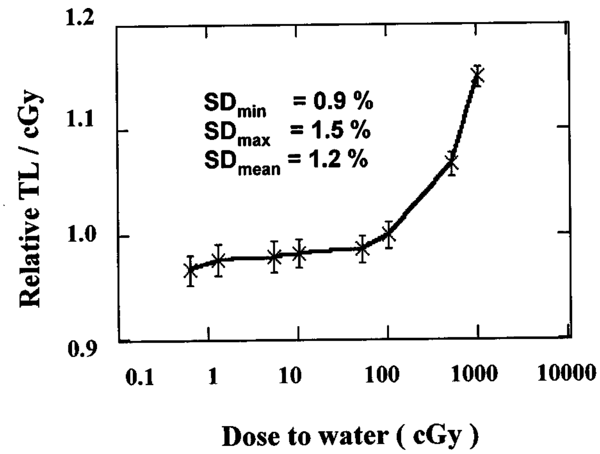

FIG. 2. The relative TLD responses to radiation dose on a semilogarithmic scale after applying the correction of the nonlinear output from the accelerator. The data were normalized to the TLD response to a dose of 100 cGy. The mean standard deviation over the eight points is 1.2% with a range of 0.9%–1.5%. The data points are the mean measurements from 5 TLD rods. The standard deviations are shown as error bars.

built-in light source containing a C^{14} (β^- emitter) embedded in a NaI crystal was checked frequently over the readout procedure at intervals not exceeding 20 readouts. The photomultiplier tube response to the light source was then plotted against the index of the sequential readout, as shown in Fig. 1. The sensitivity as a function of the sequential readout number was fitted to a second-order polynomial. Individual TLD readings were then modified according to the sensitivity obtained from the fitting function. All 180 TLDs were then assigned into five sorted groups, ranging from 26 to 50 rods with approximately the same sensitivity, to within $\pm 3.5\%$, corresponding to 1.5% standard deviation.

The above procedure was repeated once. At this step, TLDs were annealed within their respective groups according to the protocol. After readout, a few TLDs corresponding to outlier readings, or deviations of more than 2% of the group mean, were removed from each group as a refinement of the group sorting procedure.

III. RESULTS AND DISCUSSION

A. TLD linearity

Thermoluminscent sensitivity, defined as the integrated signal from the PMT per unit of radiation exposure, depends on both the characteristics of the TLDs and of the TLD reader system. The ideal response curve of a TLD would be linear over the full useful exposure range, to simplify calibration and use. The response per unit dose normalized to a radiation dose of 100 cGy for a group of TLDs, 5 for each dose, irradiated to doses from 0.5 cGy to 1000 cGy is shown in Fig. 2 on a semilogarithmic plot. The absolute TLD response demonstrated a small curvature, or nonlinearity at the dose levels higher than 100 cGy in a logarithm–logarithm plot. The mean standard deviation over the eight points was 1.2% with a range of 0.9%–1.5%. The larger standard deviations corresponded to the lower dose levels. At the lower dose levels, a small change of readout would greatly affect the relative response per cGy. Except for the nominal dose of 0.5 cGy, all TLDs were placed in the phantom at the depth of dose maximum and exposed to a chosen number of MUs. The nominal dose of 0.5 cGy (actual dose 0.62 cGy) was obtained by setting the accelerator to 1 MU and irradiating the TLD at a depth of approximately 50% dose. Nonlinearities of the accelerator output[35] up to 28% at low monitor units were observed and taken into account by measuring response per MU with an ionization chamber. The results were used to calculate the actual dose to the TLDs for the different MUs. Each datum point in Fig. 2 represented an average result of 5 TLDs, which were randomly selected from the same presorted group and then exposed to a certain radiation dose. Each reading was corrected for the sensitivity of the TLD reader and for TLD background. The background subtraction correction was very important for the lower levels of radiation dose measurement, reaching a value of 20% of the signal for the nominal 0.5 cGy dose of radiation.

The averaged relative response per cGy from six independent measurements after applying the correction for the nonlinear output is similar to that of Fig. 2, which represents data from a single set of measurements. The TL output per unit dose was practically independent of dose at dose levels up to 100 cGy, specifically 0.95 ± 0.02 for 0.62 cGy, 0.97 ± 0.01 for 5.26 cGy, 0.98 ± 0.01 at 50.0 cGy, and 1.00 at 100 cGy by definition. The smaller response per unit dose for dose levels below 10 cGy might be related to systematic factors, such as the background subtraction procedure possibly being overcorrected and the uncertain effect of the observed existence of a small residual signal after readout. The baseline signal of an unexposed TLD rod was typically in the range 0.6–1.0 nC. The actual reading was highly dependent on the annealing conditions, especially the prereadout annealing. The simple subtraction of the baseline signal may overdo the correction. At the dose level of 100 cGy, the TL signal was about 600 nC for a TLD rod, corresponding a baseline subtraction of few tenths of one percent of the signal. On the other hand, the absolute TL signal was only about 8.5 nC for the 1.3 cGy exposure, resulting in about 10% correction from the baseline signal. It was observed that the residual signal of each TLD after initial readout gave readings higher than that of the baseline reading. The reading would approach the baseline after several consecutive readouts. For a TLD rod exposed to 100 cGy, the TL signal for the second reading was about 1.5% of the initial reading.

For doses above 100 cGy, however, the response per unit dose became supralinear as seen in Fig. 2. The relative TL response per unit dose increased by 15% as dose level changed from 100 cGy to 1000 cGy. The characteristic of the curve, or the supralinearity in this higher radiation dose range has been extensively investigated and several models have been proposed to explain the behavior.[36–38]

B. TL response vs anneal time

A routine TLD measurement procedure consists of several steps, namely, high temperature annealing, low temperature annealing, exposure to radiation dose, prereadout annealing, and TL readout. There are time delays between various steps, each associated with potential TL signal loss. Understanding the effect of all these parameters associated with the different steps is important for obtaining accuracy in routine TLD measurements.

The effect of the duration of high temperature annealing on the TL signal is shown in Fig. 3(a). TLD rods from the same presorted group were divided to 4 subgroups of 7 each. The subgroups were started on the high temperature annealing process at the same time, but were terminated at different times. The TLDs then followed the rest of the standard annealing and readout procedure. The TL signal from exposure to 100 cGy of 4 MV x-ray radiation was decreased by about 8% as the duration of high temperature annealing increased from 0.5 h to 5 h. The most substantial change in sensitivity appears to occur for times below 1 h. The standard deviation of TL measurement was 1.0% for each subgroup, except that it was 2.4% for the subgroup annealed for 0.5 h at the high temperature. The larger standard deviation was possibly due to less than optimal annealing at the high temperature. Annealing time longer than 1 h resulted in reduced TL response with the same sample standard deviation. This suggests that 1 h annealing at 400 °C is sufficient for stabilizing TL response to radiation.

The effect of the duration of low temperature annealing on the TL signal was similar to that of the high temperature annealing, as shown in Fig. 3(b). Each datum point was an average result of 9 TLD rods from the same presorted group irradiated to 100 cGy of 4 MV radiation. Measurements were performed according to the standard TLD measurement except for the duration of low temperature annealing for each subgroup. The duration of the low temperature annealing ranged from 0 to 4 h. The TL signal decreased by about 35% as the duration of annealing increased from 0 h to 4 h. The most significant losses of TL sensitivity occurred for the duration between 0 and 0.5 h. Two hours of the low temperature annealing resulted in the smallest standard deviation of 1.3%. On the other hand, the standard deviation almost tripled for the duration of 0.5 h compared to that of the 2 h standard low temperature annealing time, indicating the importance of sufficient duration of low temperature annealing for reducing variation in the TLD response.

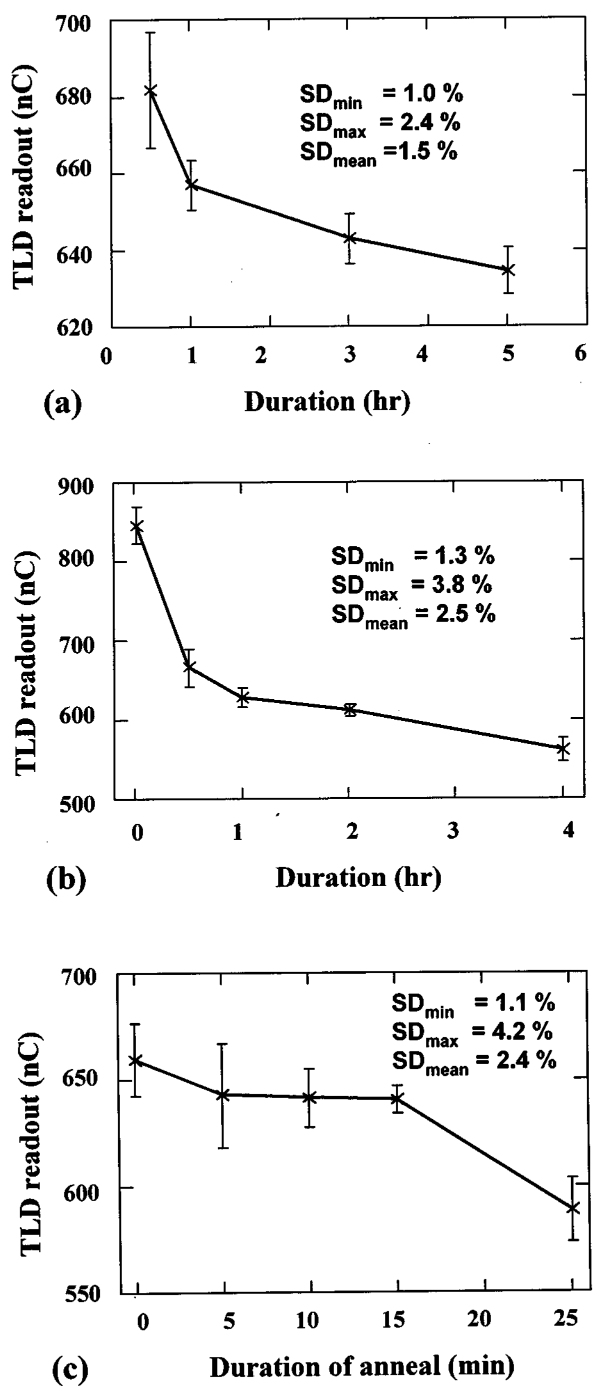

FIG. 3. The effectiveness of the duration of the annealing on the TL signals. (a) the high temperature annealing, (b) the low temperature annealing, (c) the prereadout annealing. The cross signs are the actual measurements of TLD rods with the standard deviation shown as the error bars.

The relationship between the TL signal and the duration of the prereadout annealing is shown in Fig. 3(c). TLDs from the same presorted group were annealed altogether according to the standard high and low temperature annealing procedures and were then divided to six subgroups of 5 TLD rods each, after exposure to 100 cGy of 4 MV x-ray radiation. The TL responses to radiation from one subgroup were measured without any prereadout annealing. The remaining subgroups went through the prereadout annealing at 105 °C for times ranging from 5 min to 20 min. The results shown in the figure are numerical averages of the 5 TLD readings in each subgroup. The sensitivity of TLDs to radiation showed a gradual reduction as the duration of the prereadout anneal increased to 15 min, then a 10% decrease as the duration of the annealing was increased to 25 min. For the 15 min prereadout annealing, the TL response to radiation showed the minimum standard deviation of 1.1%. For shorter duration of prereadout anneal, the standard deviations were much greater, up to almost four times, as compared to that for 15 min annealing time. This suggests that the standard 15 min prereadout annealing may remove some unstable low temperature peaks from the glow curve of TLD-100.

For the three investigations above, the results showed that the minimum standard deviation occurred approximately at the conditions of the standard annealing procedure. This may be related to the fact that these were the conditions under which the TLDs were originally presorted as a group.

C. TL response vs time delay

In a practical radiation dose measurement, TLDs are often processed according to the standard annealing procedure some time in advance before they are exposed to radiation. The stability of the TL response to radiation was examined as a function of time after preirradiation annealing. The time delay ranged from a few minutes to 190 h. For each time delay, six TLDs from one of the presorted groups were selected, and the TLDs were exposed to a dose of 100 cGy of 4 MV radiation. The prereadout annealing and readout processes were performed immediately after TLD irradiations. The data from the TLD readout were corrected for the variation in the sensitivity of the TLD reader system at the time of the readout session by the method described in the section on sorting procedures (i.e., Sec. II C). A mean standard deviation of the measurement for the time delay was 1.3%, ranging from 1.0% to 1.5%. The TL sensitivity to radiation showed a nonstatistically significant fluctuation of approximately 6%, from 575 nC to 610 nC, during the first 1.5 h, then remained virtually constant about 585 nC after that. The initial changes in the sensitivity suggest that there may be a stabilizing period of less than 1.5 h after the TLD phosphors were removed from the low temperature furnace of 105 °C and exposed to the room temperature of about 22 °C, but measurement statistics are not significant. On the other hand, the standard deviations of the TL measurements remained relatively unchanged with a mean value of 1.3% over the wide range of delays prior to irradiation after the annealing procedure. In the other words, the precision of measurement does not appear to be affected by delay of irradiation.

TL response to radiation was also examined as a function of the time interval between TLD irradiation and readout. TLDs from the same presorted group were irradiated together to a dose of 100 cGy of 4 MV radiation. At the prescheduled time from 1 h to 3 weeks, six TLD rods drawn randomly from the group went through the prereadout annealing and then readout. Each average of six TLD measurements was then corrected for the variation in the sensitivity of the TLD reader system at the time of measurement. Over a period of 3 weeks, the corrected TL reading decreased by only few tenths of one percent, which was less than the mean standard deviation of 1.2%. Presumably, then, the postirradiation prereadout annealing is effective at stabilizing the TLD signal by removing the short half-life peaks. The fact that TLDs may be read out days or even weeks after irradiation without significant losses of signal is very important for routine TLD measurements.

Another factor involved in TLD measurement is the delay that may take place at the time of TLD readout after the prereadout annealing procedure. In a busy radiation oncology department, a readout session extending over one or more hours would likely be interrupted by other clinical duties. The experiments were performed according to the standard TLD measurement protocol, except for the time variable being examined. At selected times from a few minutes to 2.5 h after prereadout annealing, six TLD rods were randomly drawn from a batch of a presorted group that had been irradiated to 100 cGy of 4 MV x rays for readout. The average TL signal did not change over a period of 2.5 h. The mean standard deviation of the measurements was 1.2%. From this measurement, one can conclude that a readout session could be interrupted after the prereadout annealing procedure without affecting the results.

D. Integrity of TLD grouping

For the TLD study taken as a whole, an initial batch of TLD rods were annealed and sorted into three subgroups of approximately equal sensitivity. The TLDs were then subjected to extensive experimentation, which included being exposed several times to a wide range of radiation from less than 1 cGy to 1000 cGy and being annealed at conditions that differed from the standard annealing procedure. It is of interest to check the integrity, or behavior of the TLD rods over the entire period of investigation which lasted several months, by examining the sample standard deviation of a group of TLDs that received a standard dose of 100 cGy and followed the standard annealing procedure. A total of 17 measurements of a dose of 100 cGy 4 MV x rays that were handled according to the standard procedure using a single presorted subgroup were available. Each datum represented a measurement that averages the data from 5 or 6 TLDs. Averaged over all measurements, the mean value of the percent standard deviation was 1.1%, ranging from 0.6% to 1.6%. There were no signs of any change in precision of the TLD grouping over the measurement period during which some

TLD rods might have received more than 10000 cGy and received approximately 30 annealing cycles. These data confirm the robustness of the group annealing and sorting procedure. We observed, as noticed by Cameron *et al.*,[38] that the absolute TL response to the same radiation dose was gradually reduced. The sensitivity declined about 0.9% per 1000 cGy. The reduction in sensitivity was thought to be due to radiation damage in Cameron's study and was dependent on the amount of radiation dose. As the differences in doses received by individual TLDs from the same group increased significantly, the relative change in sensitivity would increase the standard deviation of a particular measurement. When this occurs, it is time to repeat the group annealing and sorting process. In our experience, however, another batch of TLD-100 rods still held their integrity as a group after more than 2 years of intensive clinical use.

IV. CONCLUSIONS

We reported here the group annealing and sorting (GAS) procedure for routine TLD radiation dose measurement. This simplified TLD technique is characterized by high precision and reproducibility of radiation dose measurement, achieved without identifying individual TLDs and without flushing the planchet heater with nitrogen gas during the readout session. In dose levels ranging from 0.6 cGy to 1000 cGy, the measurement of 5 TLD rods resulted in an average readout standard deviation of 1.2%. Response per unit dose was almost flat over the range from 0.6 cGy to 100 cGy, and increased by 15%, i.e., supralinearly, over the range from 100 cGy to 1000 cGy. The sorted group held its integrity very well after being subjected to intensive radiation dose measurements.

TL response to radiation dose decreases with increasing duration of the high temperature, low temperature, and prereadout anneals. The chosen annealing duration for each step in the procedure that we have labeled as the standard procedure is adequate to stabilize the sensitivity of TLDs to radiation without substantial loss of TL signals. The results of TLD readout are relatively independent of time delay (i) between irradiation of TLDs and readout, (ii) between the end of the low temperature annealing and irradiation of TLDs, and (iii) between the prereadout annealing and readout. In the other words, the group sorting provides the precision of TLD measurement without the tedious tasks of individual TLD identification, while the prereadout annealing improves the accuracy by removing the unstable low temperature peaks. GAS procedure provides a simple, reliable, precise, convenient, and accurate method for TLD measurements.

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