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Research Article

Thermoluminescent Detectors to Measure LET in Proton Beams

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Abstract

In this study the ratio of the two High Temperature Peaks (HTR) in TLD700 glow curves is used to investigate the spatial dependence of the linear energy transfer (LET) in proton beams. Studies show that the Relative Biological Effectiveness (RBE) depends upon the physical dose as well as its spatial distribution. Glow curve analysis of TLD700 shows that the 280 C temperature peak is more sensitive to LET radiation than the 210 C temperature peak. Information on LET can be obtained from then HTR by normalizing the areas under the individual temperature peaks for TLDs irradiated in a proton beam with a range of 6.1 cm normalized to the HTR for low LET 6 MV photons to determine the HTR to obtain information on its LET. Six TLD700 chips with dimensions 0.32x0.32x0.38 cm^3 were placed in a specially designed blue wax phantom at six different depths of the Percent Depth Dose Curve (PDD): center of the SOPB and approximately at the 100% distal edge, 90%, 80%, 50% and 20% of the PDD, respectively. Measured HTR was 1. 6 at the center of the SOBP and varied from 2.4 to 3.7. Using a calibration curve this can be related to LET *via* a calibration curve to an LET variation from 1.5 to 16.4 keV/µm. The HTR data show a spatially invariant LET slightly greater than the 6 MV radiations in the SOBP, but a rapidly increasing LET at the end of the proton range. These results validate through direct measurements the spatial variation in LET across a clinical proton beam that could be used to predict variable RBE effects in actual treatment plans.

Keywords: Protons; Thermoluminescent detectors; Linear Energy Transfer and relative biological effectiveness

Introduction

Thermoluminescent Detectors (TLDs) are used in health physics and radiation therapy because of their unique physical and dosimetric characteristics [1]. As a relative dosimeter, they require calibration, ideally at the same beam quality used for their measurement, to relate their signal to absorbed dose. TLD measurements require an analysis of the glow curve by measuring the light output as a function of temperature. The glow curve generally consists of multiple peaks and the majority of the measurements involve integrating the total light output under the peaks or using the main peak height of the glow curve to relate the measured signal to absorbed dose through a calibration. However, studies have shown that the high temperature 285 C peak in TLD 700 glow curve is more sensitive to the Linear Energy Transfer (LET) radiation than the lower 210 C peak [2]. The High Temperature Ratio (HTR) can be obtained independently calculating the areas under these two peaks and taking the ratio of these areas. It has shown that the HTR is directly related to the LET [3,4]. Therefore, it is possible to use the different sensitivities of TLDs to directly measure the spatially dependent LET distributions of particle radiations. In proton therapy studies have shown that the amount of biological damage depends on both the absorbed dose and the Relative Biological Effectiveness (RBE), which is related to the LET of the radiation [5,6] among several other factors. For patient treatments, a mono-energetic proton beams is of limited clinical value owing to the narrow region of high dose in the Bragg peak. By summing a distribution of decreasing energies of decreasing intensity, a uniform region of dose can be produced at the depth and width of the target within the patient. This is commonly known as a Spread Out Bragg peak (SOBP). Protons in the more proximal portion of the SOBP are of higher mean energy while the protons in the distal portion of the SOBP have a greater proportion of lower energy, and thus, a higher LET. This results in a variation of LET along the SOBP of the proton beam. In this study TLD700 chips are inserted in a water-equivalent plastic phantom to measure the absorbed dose and LET at several points along the proton beam including the plateau region of the SOBP, the proximal edge of the SOBP, and in the distal edge of the SOBP. The HTRs, which then can then be used to infer the LET of the protons, are obtained by determining the areas under the high and low temperature glow curves. The HTR is related to the LET through a calibration curve.

Materials and Methods

The dimensions of the LiF TLDs used in this study were 0.32x0.32x0.038 cm^3. The relative sensitivity of the high and low temperature peaks for each detector was obtained by reading out their signal with a Harshaw 5500 TLD reader (Thermo Fisher Scientific) following irradiation to 30 cGy with 6 MV photons. The TLD reader uses a computer controlled hot nitrogen gas to heat the detectors. The glow curve was obtained by measuring the light output from 100 to 300 C at a heating rate of 10 C/s. The detectors were then annealed for 1 hour at 400 C followed by an 18 to 24 hour anneal at 80 C.

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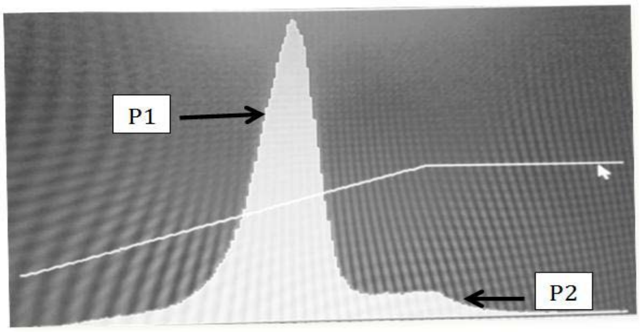

Figure 1: Glow curve obtained for a TLD irradiated to an absorbed dose of 20 cGy in a clinical proton beam illustrating the two temperature peaks. P1 represents the lower temperature peak and P2 is the higher temperature peak.

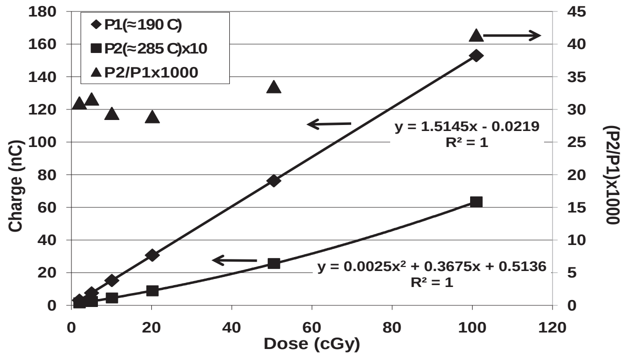

Figure 3: The TLD dose response of peaks P1 and P2 to 6 MV photons illustrating the sensitivity differences between the two peaks. P2 exhibits supralinearity above about 30 cGy.

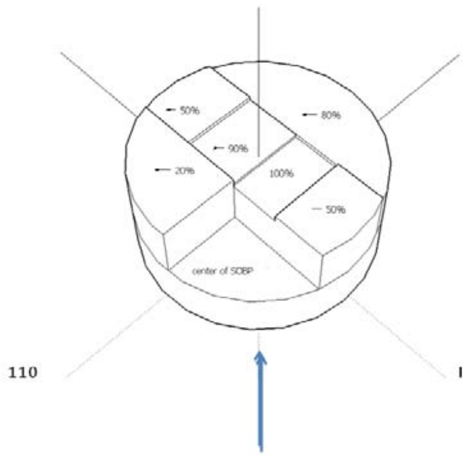

Figure 2: Schematic diagram of the cylindrical phantom used for measurements along the proton beam showing the location of the TLD700 detectors at the various depths. The arrow indicates the direction of the incident proton beam.

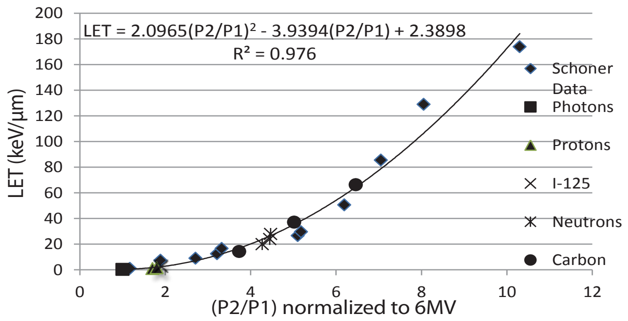

Figure 4: Graph showing the relation between LET and measured HTR normalized to the ratio of 6 MV obtained from measurements in beam qualities of various LET. The Schoner [3] data are also shown on the graph. Dose averaged LET values for the neutron and carbon beams were obtained from the institutions, and the proton LETs were obtained from the institution's Monte Carlo calculations. The uncertainties in the measured HTR to LET values are estimated to be ±4% at 1SD as described in the uncertainty section.

This annealing protocol was strictly followed to obtain a glow curve similar to the one shown in Figure 1 that allowed for determining the area under the two peaks.

This irradiation, read-out, and anneal procedure was repeated three additional times to obtain an average sensitivity for each detector that varied by less than ±2% and ±3% for the low and high temperature peaks, respectively. The greater variation of the high temperature sensitivity was due to the lower signal to noise read-out of this peak. Over the course of this study their sensitivities were measured and remained within the 2% and 3% variation for the 210 and 285 C peaks, respectively.

All proton irradiations were performed at the Northwestern Medicine Chicago Proton Center (NMCPC). Protons are accelerated using a C230 Cyclotron manufactured by Ion Beam Applications (IBA). The irradiations were performed using IBA's universal nozzle in the uniform scanning mode. Measurements were performed in a nearly water-equivalent blue wax phantom used for making patient treatment compensators. It was machined to accept the TLDs at water-equivalent scaled depths (Freeman Manufacturing and Supply Company, Avon, OH). The blue-wax material has a water-equivalent thickness of 0.977 and a mass density of 0.92 g/cm^3. A cylindrical slab phantom was used for irradiating up to six TLDs at each fixed depth. The effective depth of the TLDs could be adjusted by adding additional water-equivalent slabs to the front of the phantom. The front cover of the slab phantom included 1.0 cm of inherent water-equivalent thickness. Figure 2 shows a schematic diagram of the slab phantom slices containing TLDs used for measurements at various depths in the plateau region and throughout the SOBP. The TLD700 detectors were positioned in each individual slab of the cylindrical phantom for these measurements.

The TLDs in this phantom were placed at depths at the center of the SOBP (depth = 3.0 cm) and at depths approximately at 100, 90, 80, 50 and 20 percentage depth doses for a proton irradiation of range 6.1 cm and modulation of 6 cm. At NMCPC range is defined at the distal R90 (range of 90% depth dose). Field modulation is defined as the distance between the distal R95 (range of 95% depth dose) and the proximal R95 of the SOBP. This phantom was irradiated three separate times to determine the HTR/LET in the SOBP and in the dose fall off region of the Bragg peak. The average values of the TLD readings were used in the analysis. The HTRs for the TLDs exposed in the proton beam at various depths in the phantoms were determined

Table 1: Summary of three separate irradiations showing the variation of HTR/LET in center of the SOBP and in the distal fall-off region for protons of range 6.1 cm and modulation of 6 cm.

WET†(cm)	R(res)*(cm)	~PDD	HTR‡ $(P2/P1)_{6MV}$	LET (keV/µm
3	3.1	Center of SOBP	1.62 ± .04#	1.51 ± .12‖
5.9	0.2	100	2.44 ± .03	5.26 ± .19
6.1	0	90	2.73 ± .04	7.26 ± .30
6.2	-0.1	80	3.00 ± .05	9.44 ± .41
6.3	-0.2	50	3.34 ± .07	12.6 ± .70
6.5	-0.4	20	3.69 ± .11	16.4 ± 1.2

* Water Equivalent Depth;
† Residual rangesare distances to the R90 with negative values representing distances past;
the prescribed range;
‡ High temperature ratios;
# Standard deviation from three separate measurements;
‖ Uncertainty estimated from using the standard deviation from the HTR measurements in equation (1).

from the glow curves. These values were normalized to the HTRs for TLDs irradiated in a low LET 6 MV photon beam using a Varian True Beam linac. To relate the measured HTRs to LET, TLDs were irradiated in beams of various LETs: the carbon beam at Japan, the neutron beams at the University of Washington, Fermi National Accelerator Laboratory (FNAL), and Wayne State University, and proton beams at NMCPC and MD Anderson Cancer Center.

Results

The dose response of the two peaks in TLD700 is shown in Figure 3 and illustrates the difference in the response and sensitivities between the two peaks. In particular P2 shows a supralinear response beyond 30 cGy while the P1 response remains linear up to 100 cGy.

The high temperature peak response begins to exhibit supralinearity above about 30 cGy consistent with previously published data [7]. Therefore, to remain in the linear region of the TLD response, the absorbed doses to the TLDs in all the irradiations were kept below 30 cGy. Irradiating the TLDs in this dose region produced glow curves similar to Figure 1 that allowed for separating the peaks to determine the area under the individual peaks. The HTR as a function of LET obtained from irradiations in beams of various LET (carbon beam at Japan, the neutron beams at the University of Washington, Fermi National Accelerator Laboratory (FNAL), and Wayne State University, and proton beams at NMCPC and MD Anderson) is shown in Figure 4.

The HTR values are normalized to the value for the low LET 6 MV photons. The different symbols represent the different beam qualities used to obtain a calibration curve relating the measured HTR ratios to LET. Also included in the plot are the HTR values published by Schoner et al. [3]. A second order polynomial shown on the plot was used to fit all the data and is given by equation

(1) $\mathrm{LET} = 2.096(P2/P1)^2 - 3.939\,(P2/P1) + 2.390.$

From the irradiations in these beams the LET dependence of the total integrated TLD signal normalized to 6 MV photons were determined and presented in Table 1.

This table summarizes the three separate phantom irradiations showing the variation of the HTR/LET at the center of the SOBP and at the different depths in the distal fall-off region of the Bragg peak.

Table 2: Estimated relative standard uncertainty (%).

Uncertainty Quantity	Type A	Type B
TLD reproducibility	2	
Reader stability		0.3
Reader linearity-6 MV		1
$(P2/P1)^{proton}{}_{6MV}$4.0 LET*	4 to 8	
Equation relating HTR to LET†	4	
Combined uncertainty (k=1)	7.2 to 10.0	1
Total uncertainty (k=1)	7.3 to 10.0	

* Range of uncertainties calculated by propagation or errors analysis.
† Estimated uncertainty calculated using the statistical procedure of leave-one-out.

Discussion

The critical aspect of this work is relating the measured HTR of the TLDs to the LET shown in Figure 4. Also shown on this plot are the data from the Schoner [3] study that are normalized to ^{60}Co, and are consistent with our results. A second order polynomial was used to fit all of the measurements to relate the measured HTR values to LET. For these irradiations, the LET dependence of the total integrated TLDs signal per absorbed dose normalized to 6 MV photons was also obtained. In Table 1 LET values are presented for measurements in the SOBP as well as in the region of the distal falloff of the Bragg peak for protons of range 6.1 cm and modulation of 6 cm. The HTR values are the average of three separate irradiations and the approximate percent depth doses are included for the TLDs at the depths distal to the Bragg peak. The LET for the detector in the SOBP is typically what is expected and relatively constant throughout the SOBP. LET for the detectors distal to the SOBP exhibit a large increase with depth and LET from 5. 26 to 16. 4 keV/µm. This rapid increase in LET is attributed to the relatively larger portion of lower energy protons in this region. These results are consistent with LET values of greater than 10 keV in the distal falloff proton fields reported by Grassberger et al. [8] as well as those reported by Loncol et al. [9-11]. The important TLD characteristic used in this study is that the high temperature peak has an increased sensitivity to high-LET radiation relative to the low temperature peak. Zullo et al. [12] published results showing good agreement between ionization chamber measurements and TLDs in the SOBP and in the distal fall-off region of a proton beam. An important assumption of this study is that the variation of the LET for protons traversing the TLD is negligible. This assumption is valid for the higher energy protons in the SOBP region; however it is probably not valid in the more distal Bragg region at the end of the proton range. Therefore, LET values obtained from measured HTRs in this region have a greater uncertainty.

These results support the use of measuring the HTR in TLDs to estimate the variation of LET over the proton range. The spatial variation in LET over the proton range can potentially affect treatment-planning strategies where a spatially invariant LET and a constant RBE of 1.1 is assumed.

Uncertainties

The uncertainties provided in the tables and figures are obtained from determining the variation in the individual TLD sensitivities and the uncertainty in obtaining the relation between the HTR and LET. The source of the measurement uncertainties are summarized in Table II and are listed as type A or Type B uncertainties. They are obtained from the TLD reproducibility, TLD reader properties, ratios of P2/P1 (HTRs), uncertainties in the LET values, and the relation between LET and HTR. The uncertainties in the HTRs are obtained from the average of 6 or 12 measurements.

Conclusion

As of now there are no radiation detectors available to easily and accurately measure the LET in particle beams. The RBE of radiation depends upon a number of factors such as its LET, tissue type, cell cycle, biological end point and oxygenation level to name a few. Information on the spatial variation of the LET and dose deposition of particle beams could provide useful information for more advanced treatment planning strategies in particle radiotherapy [13]. In this study the LET dependence of the two high temperature peaks in the glow curve of LiF TLDs, is used to measure the spatial variation of the LET in proton beams. It is important to emphasize that relating the measured HTR to the LET depends upon the accuracy of obtaining the HTR dependence on LET via irradiation of the detectors in radiation beams of known LET. The measurements show that there is a relatively small spatial variation from 0.74 to 1.60 keV/μm in the proton LET proximal and within the SOBP. However, near the distal falloff of the SOBP there is a rapid increase in the LET from about 5.26 to 16.4 keV/μm. The spatial variation in LET and therefore RBE is generally not considered in determining clinical treatment margins. However, the rapid increase in LET distal to the SOBP in therapy proton beams should be carefully evaluated.

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