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Monte Carlo simulation of TLD response function: Scattered radiation field application

Alireza Shirazi[1ADEFG], Seied Rabie Mahdavi[2ABDEF], Ali Khodadadee[3BCE], Mostafa Ghaffory[4BCD], Asghar Mesbahi[5CD]

[1] Depertment of Biophysics, Faculty of Medicine, Medical Sciences, University of Tehran, Tehran, Iran
[2] Depertment of Biophysics-Biochemistry, Babol University of Medical Sciences, Babol, Iran
[3] Azad Research and Science University, Tehran, Iran
[4] Secondary Standard Dosimetry Laboratory (SSDL), Iranian Organization of Atomic Energy, Karaj, Iran
[5] Depertment of Medical School, Tabriz University of Medical Science, Iran

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A Study Design
B Data Collection
C Statistical Analysis
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Summary

Aim

Thermoluminescent dosimeters (TLDs) have various applications in non-primary beam dosimetry. Monte Carlo simulation of TLD response was done in low energy beams to improve its clinical use in scattered beam dosimetry.

Materials/Methods

TLD material made from LiF doped with Mg and Ti sized $3.1\times3.1\times1mm^3$ was used for experimental measurements as well as modelling by MCNP-4c Monte Carlo simulation. TLDs were irradiated for different doses of beam qualities ranging from 120, 180, 200, 250 to 300kVp x-rays generated from an orthovoltage machine and 1.25MeV gamma rays from a Co-60 teletherapy unit at reference depth in a water phantom. The simulation conditions were the same as experimental conditions. The calibration factor, *(CF)q*, and its quality dependence factor, (F^X_{Co}), were defined as:

$$(CF)q = \text{Calibration Dose/TL},\ (F^X_{Co}) = \frac{TL(X)/D_{med}(X)}{TL(X)/D_{med}(Co)}$$

Results

The normalized values of measured quality dependence factors for different x-ray beams were 1.28, 1.24, 1.16, 1.07 and 1.03 for different beam qualities, respectively. Comparatively, the MCNP simulated findings were 1.134, 1.96, 1.139, 1.052 and 1.034. The change of calibration factor with energy followed the equation $CF=B_0+B_1E+B_2E^2+B_3E^3$, where CF and E are calibration factor and energy (keV), respectively. B_0, B_1, B_2, B_3 are constants.

Conclusions

Our findings showed significant deviation of true dose value when TLDs are calibrated at different beam qualities. The greatest deviation was 19.9±2.1% in beam quality of 120kVp. Obtaining a dose response curve may be helpful to calculate the calibration factor with more precision.

Key words **TLD response • calibration • quality dependence • MCNP**

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Author's address: Alireza Shirazi, P.O. Box 14145-468, Tehran, Iran, e-mail: shirazia@sina.tums.ac.ir

BACKGROUND

Thermoluminescence dosimetry (TLDs) is routinely used for *in-vivo* dosimetry as well as other applications in medicine and industry [1,2]. The most commonly used TLD material is lithium fluoride doped with small quantities of Mg and Ti, denoted by LiF: Mg,Ti (TLD-100). This popularity is due, in part, to approximate tissue equivalence and low signal fading [3].

Knowledge of TL response, especially at commonly used photon energies, is useful to estimate the uncertainty of the dosimetry system, and experimental methodology has elsewhere been regarded as the most reliable option [4].

TLDs are relative dosimeters and therefore have to be calibrated against absolute dosimetry systems such as a calibrated ion chamber. In radiotherapy application it is common to calibrate them in a ^{60}Co γ-ray beam or in a low-energy megavoltage x-ray beam of ^{137}Cs γ-rays [4,5]. It is therefore important to know the quality dependence and energy correction factors that should be applied if the TLDs are used in photon beams other than a calibration beam such as scattered beams [4].

In the present study, quality dependence of TLD-100 response was measured in different beam qualities followed by MCNP simulation. It was done to model the behaviour of dosimetry at low energy x-ray beams to improve the TLD usage in a scattered radiation field.

MATERIALS AND METHODS

We used forty cubic chips of lithium fluoride (LiF) crystals doped with magnesium (Mg) and titanium (Ti) presented at concentrations of 200 and 10 ppm by weight, respectively. Chip sizes were 3.1×3.1× mm^3 with density of 2.64g cm^{-3} and were manufactured by Harshaw company. Our protocol for using TLD-100 was described in detail by Mckeever [2]. Briefly, the chips were first annealed at 400 °C for 1h, followed by a second annealing at 100°C for 2h. After irradiation, and before reading, the TLDs were stored for 24h at room temperature (20°C) to clear the low energy traps. To produce radiation beams with different energies, Co-60 radiotherapy and orthovoltage x-ray therapy machines were used as specified in Table 1.

Table 1. Specifications of X or γ-ray beams that were used for measurements and calculations in this research.

(Radiation qualities)		Mean energy (MCNP)
(Applied Kilovoltage)	(HVL)	
120kVp	0.2mm Cu	58keV
180kVp	0.5mm Cu	74keV
200kVp	1.0mm Cu	88.6keV
250kVp	2.0mm Cu	114.5keV
300kVp	3.2mm Cu	140.2keV
1.25MeV (average Co-60 energy)	1.1mm Pb	1.08MeV

To determine the sensitivity of each individual TLD, efficient correction coefficients (ECC) were obtained by the following equation after irradiation on a Perspex holder.

$$Ecc_i = \frac{\mathrm{Ri}}{\bar{R}} \qquad (1)$$

where ECC_i is the ECC of each TLD, $\bar{R}$ and Ri are individual reading and average reading of the total TLDs, respectively.

The TLDs were calibrated against an ionization chamber at depth of 5cm of water phantom at a distance of 50cm from the radiation source. Water absorbed dose of ^{60}Co γ-rays was measured by using IAEA protocol 277 [6]. To obtain absorbed dose calibration factors in cGy/Count, TLD chips in groups of three or four were irradiated with different beam qualities (120–300kVp). Then, the average counts (corrected for background counts) of the TLDs at each dose group were determined. Calibration factor at each energy quality was defined as the inverse of the tangent of TLD absorbed dose response curve. This factor allows the TL signal to be converted to the received dose:

$$(CF)_q = \text{Calibration Dose/TL} \qquad (2)$$

where "calibration dose" is the given dose for calibration of TLD and TL is the dosimeter response in coulombs after irradiation with beam quality of "q" [7]. The quality dependence factor (F^X_{Co}) is then defined as:

$$(F^X_{Co}) = \frac{TL(X)/D_{med}(X)}{TL(Co)/D_{med}(Co)} \qquad (3)$$

where $TL(X)/D_{med}(X)$ is the light output of material TL per unit dose for the x-ray beam quality or inverse of calibration factor for each beam quality. $TL(Co)/D_{med}(Co)$ is the light output per unit dose in the same medium for ^{60}Co gamma-rays or the inverse of the calibration factor for the ^{60}Co gamma-rays. Assuming the D_{LiF} to be the dose of TLD material that is directly proportional to the output light of TL(X) at any x-ray beam quality, (F^X_{Co}) can also be written as:

$$(F^X_{Co}) = \frac{(D_{med}/D_{LiF})_{Co}}{(D_{med}/D_{LiF})_X} \qquad (4)$$

To measure the absorbed dose cavity theory defines the relation between the dose absorbed in a medium D_{med} and the average absorbed dose in the detector or cavity $\bar{D}_{cav}$:

$$D_{med} = \bar{D}_{cav} : f_{med,\, cav} \qquad (5)$$

where f_{cavmed} is a factor that varies with energy, radiation type, medium, size and composition of the cavity. For a cavity that is large enough in comparison to the range of electrons, the dose in the medium can be obtained from the mass energy-absorption coefficient ratio of that medium to the cavity material:

$$f_{med,\, cav} = \left(\frac{\mu_{en}}{\rho}\right)_{med,\, cav} \qquad (6)$$

where $\left(\frac{\mu_{en}}{\rho}\right)_{med,cav}$ is the ratio of the mass-energy absorption coefficient of medium to the cavity, averaged over the photon energy fluence spectrum present in the medium. This expression completely neglects any perturbation effects or interface effects that may occur by the introduction of the detector material into the uniform medium [8]. As a consequence, for kilovoltage x-rays the dose ratio of water to LiF is equal to the mass energy-absorption coefficient of water to Lif. This is justified as the range of electrons generated by kilovoltage x-rays are very short compared to the smallest distance across the cavity in the beam direction. From equation 5 quality dependence was re-designed as:

$$\frac{((\mu_{en}/\rho)_w/(\mu_{en}/\rho)_{LiF})_{Co}}{((\mu_{en}/\rho)_w/(\mu_{en}/\rho)_{LiF})_Q} \qquad (7)$$

The mass energy absorption coefficients for water and LiF are taken from Hubble(1982) [9].

Monte Carlo simulation

MCNP-4C Monte Carlo system was used for all simulations reported in this study. Monte Carlo calculation did not show any difference in behaviour of pure LiF and TLD-100 in kilovoltage or megavoltage x-ray ranges. This is expected since the concentration of Ti and Mg by weight is negligible in TLD-100 [10]. The TLD chips were represented by a 3.1×3.1×1mm cube. In all cases the phantom material was also represented by a 20×20×12cm cube of water such as the experimental method. The incident photons were transported in a water medium and the dose scored in a water cube of the same dimensions as the TLD placed with its centre at a particular depth. The depth of irradiation of the TLD in kV x-rays and ^{60}Co gamma-rays was 5cm. We used energy cut-off variance reduction technique in this simulation. Electron and photon transport were terminated at 10keV and 1keV, respectively. The photons were assumed to be perpendicularly incident on the flat surface of the chip. Non-divergent beam and field size of 6×8cm were applied to simulate the experimental method. The recent publishing photon beam spectra for a theratron 780 E cobalt machine was also used as input. Kilovoltage spectra were taken from the results of our previous investigation.

The mean energies of the simulation shown in Table 1 were calculated from the expression:

$$E_{mean} = \left(\sum_l^n \phi(E_i) E_i \Delta E_i\right)\left(\sum_l^n \phi(E_i)\Delta E_i\right)^{-1} \qquad (8)$$

where E_i is the phantom energy and ϕE_i is the number of photons in the energy bin of width ΔE_i at the phantom surface. The uncertainty was estimated by dividing the calculations into ten batches as well as calculating the variance on the mean. Each simulation was terminated

Table 2. Calibration factors of different x-ray qualities were tabulated.

Photon specifications		Calibration factor (cGy/Count)
Qualities	HVL	
120kVp	0.2mm Cu	0.00718
180kVp	0.5mm Cu	0.00740
200kVp	1.0mm Cu	0.00795
250kVp	2.0mm Cu	0.00862
300kVp	3.2mm Cu	0.00894
1.25MV (Co-60)	1.1mm Pb	0.00923

Table 3. Experimental quality dependence factors and their respective energy correction factors against Co-60 calibration factor were tabulated.

Beam quality	HVL	Quality dependence factor	Correction dependence factor
120kVp	0.2mm Cu	1.28	0.70
180kVp	0.5mm Cu	1.24	0.80
200kVp	1.0mm Cu	1.16	0.86
250kVp	2.0mm Cu	1.07	0.93
300kVp	2.5mm Cu	1.03	0.97
1250keV	1.1mm Pb	1.00	1.00

when the uncertainty reached lower than 1% and for this it needed between 3×10^7 and 2×10^8 x-ray photons.

Results

The calibrated Siemens Stabilipan II superficial/orthovoltage therapy unit was used to irradiate TLDs with kilovoltage therapy beams as shown in Table 1. Table 2 shows the calibration factor values of the TLDs which were obtained as explained in the method section. Table 3 demonstrates the experimental quality dependence factor of different x-ray qualities and ^{60}Co gamma rays. The data in Table 3 show the experimental quality dependence factors of TLD at different beam qualities. Calculating the absorbed dose to water for different test beams based on the ^{60}Co calibration factor shows some deviations in comparison to the related beam calibration factor. Table 4 shows the deviation between calculated absorbed dose to water based on ^{60}Co calibration factor. Maximum deviation was observed in the 120kVp irradiation field.

Table 4. The mean ±SD of error absorbed dose to water reading of TLDs at different beam qualities when they are calibrated with the energy of Co-60 ($p<0.02$).

Qualities	HVL	D_w/D_{LiF} (MonteCarlo)	D_w/D_{LiF} (Cavity theory)
120kVp	0.2mm Cu	0.91	0.97
180kVp	0.5mm Cu	1.00	1.05
200kVp	1.0mm Cu	1.05	1.09
250kVp	2.0mm Cu	1.13	1.15
300kVp	2.5mm Cu	1.16	1.17
1250keV	1.1mm Pb	1.196	1.20

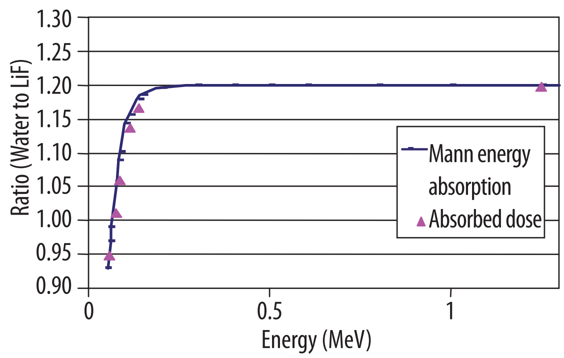

Figure 1. TLD-100 in kV x-ray beams and ^{60}Co gamma rays: comparison of the Monte Carlo derived dose ratio, water to LiF, with the mass energy – absorption coefficient ratios, as a function of the maximum tube voltage in kV beams and ^{60}Co gamma rays.

For calculation of Monte Carlo quality dependence factor, we obtained the ratio of absorbed dose in water and LiF (cavity) (D_w/D_{LiF}). Figure 1 shows the changes of the mass energy – absorption coefficient ratio and the Monte Carlo calculated dose ratio of water to LiF from 120kVp to 1250keV x-ray beams. It shows that the experimental calibration factor varies with the Monte Carlo calibration factor (D_w/D_{LiF}).

The low and medium energy radiation of orthovoltage and superficial Siemens Stabilipan were simulated by Monte Carlo calculation. The ratio of absorbed dose scored in water and LiF TLD (D_w/D_{LiF}) were also calculated by Monte Carlo method. We obtained the theoretical prediction of (D_w/D_{LiF}) by the definition of cavity theory for LiF TLDs. Table 5 shows the different values of (D_w/D_{LiF}) obtained from Monte Carlo calculation and theoretical prediction by means of cavity theory for different beam qualities. In Table 6 the results of the quality dependence factor obtained from Monte Carlo calculation,

Table 5. The ratio of absorbed dose in water and LiF TLDs by Monte Carlo calculation and prediction of cavity theory are shown.

Qualities	Quality dependence factor	Quality dependence factor (MonteCarlo)	Diff.(%)	Quality dependence factor (Cavity theory)
120kVp	1.28	1.134	−11.41	1.237
180kVp	1.24	1.96	+58.06	1.142
200kVp	1.16	1.139	−1.81	1.100
250kVp	1.07	1.052	−1.68	1.043
300kVp	1.03	1.034	+0.04	1.018
1250keV	1.00	1.00	0.00	1.000

Table 6. Value of quality dependence factors obtained by measurement, Monte Carlo calculation and cavity theory are shown. Percentage differences between measured values of quality factors and MCNP calculated factors are also tabulated.

Qualities	HVL	Mean diff.(%)	Standard deviation
120kVp	0.2mm Cu	19.9	2.1
180kVp	0.5mm Cu	13.78	4.0
200kVp	1.0mm Cu	8.46	3.51
250kVp	2.0mm Cu	3.60	2.64
300kVp	2.5mm Cu	1.25	1.14
1250keV	1.1mm Pb	–	–

experimental study and cavity theory method are compared. The differences between experimental and MCNP values were also determined. It is illustrated that calculated values of quality dependence factor by Monte Carlo and cavity theory predictions are more comparable at higher mean energies.

Discussion

Precision in TL dosimetry is very critical when the quality of radiation is to be considered. It is generally accepted that ±5% uncertainty in dose delivery to the target volume can be considered as a safe limit causing no severe radiotherapy treatment consequences [11]. The quality dependence factor is necessary if LiF TLDs are calibrated using a ^{60}Co photon beam but are used in lower or higher energy photon beams.

In dosimetry it is frequently assumed that the quality dependence of thermoluminescence LiF: Mg,Ti detectors such as TLD-100 follows the ratio of the energy absorption coefficient for the LiF and water. It has been shown by Mobit et al. (1998) that the quality dependence factor for LiF-TLD in kilovoltage x-rays relative to ^{60}Co gamma-rays ranges from 1.36 for 50kV x-rays to 1.03 for 300kV, which are comparable with our results [10]. Kearfott et al. (1990) observed a quality dependence factor of LiF TL ribbon from 1.045 (50keV) to 1.353 (100keV) [12]. The study of Kron et al. (1998) also showed the quality dependence factor of 1.47 at 27keV from synchrotron radiation [4]. Esteban et al. (2003) reported results from experimental and cavity theory studies of LiF TLD in 20–29 photon beams, where the measured value of correction factor (approximately 0.78) is more comparable to the value determined from cavity theory for the effective energies of 25keV and 29keV [13].

We experimentally obtained the absorbed dose calibration factor (CF) for the x-ray range of 120 to 1250keV. The calibration factor varies from 0.00718 to 0.00923 cGy/count for 120–1250keV and quality dependence factor was in the range of 1.000 to 1.28 for Co-60 to 120kVp x-rays respectively (Table 3). This shows that quality dependence factor decreases with increasing beam energy and it reaches the level of the normalized one (in this case to the CF of Co-60). This is an important point for dosimetry outside the primary radiation field. TLDs are used for dosimetry of scattered radiation and in such cases the calibration factor quality dependency may be a major consideration.

The dose ratio of water to LiF (D_w/D_{LiF}) and the mass energy absorption coefficient ratio were found to be more comparable with increasing mean energy. This is reasonable because with increasing energy added filtration also increased and the low energy portion of the spectrum is filtered out so that values of (D_w/D_{LiF}) obtained by the two methods are more comparable. The same phenomenon was experienced by Esteban et al. for LiF-TLD [13]. Quality dependence factors obtained from the Monte Carlo method are in good agreement with the experimental method except for 180kVp and to a lesser degree for 120kVp. The difference between quality factors at 180kVp is about 3.5%, which may be due to more exposure rate beam quality so that made its control more difficult. There is a significant difference of quality dependence factors between cavity theory and Monte Carlo quality dependence factors. As shown this difference decreases with increasing beam filtration. The same effect was also reported by Esteban et al. (2003), which may be explained by attenuation of low energy photons [13].

Modelling the calibration factor of detectors can be used to predict the quality dependence factor. This model is to provide a tool for evaluation and not a physical explanation for the calibration factor. The energy model decreases with decreasing energy. The change of calibration factor with energy followed the equation:

$$CF = B_0 + B_1E + B_2E^2 + B_3E^3 \qquad (9)$$

where CF and E are calibration factor and energy (in keV), respectively. B_0, B_1, B_2 and B_3 are 0.0058, 1.8E-5, 1.3E-8 and 0.12. Equation 9 was fitted to the changes of calibration factors for different beam qualities.

Low energy x-rays are the major part of the scattered radiation which may arise partly from the primary irradiation field and partly from any scattering medium in the path of the primary beam. Using the data of the curve over the low energy range based on equation 9 can lead to more precise results in TL dosimetry. Our findings also showed a significant difference between dose values when TLDs are calibrated in a Co-60 beam. The greatest difference was equal to 19.9±2.1% for beam quality of 120kVp.

Conclusions

In conclusion, our study showed that the quality dependence of TLDs should be considered if LiF is calibrated in a different beam quality than one actually wanted to use. Dosimetry of non-primary radiation fields needs more attention because of the contribution of a wide range of low energy photons to dose formation. Obtaining a dose response curve may be helpful to calculate the calibration factor with more precision. The simplest way is to calibrate the chips against an ionization chamber using the beam quality that is to be used for the measurement.

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