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Investigation of the energy response of thermoluminescence dosimeter used for measurement of individual dose-equivalent

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HIGHLIGHTS

- TLD response depends on the photon energy.
- There are only two standard photon fields of Cs-137 and Co-60 for calibration in Iran.
- Energy response of personal TLD is calculated and validated with measurements.
- The response below 0.4 MeV needs to be corrected.

ABSTRACT

One of the challenges of individual dosimetry in Iran is the absence of standard radiation fields with different energies for calibration. For dosimetry in the photon fields, only the standard fields of Co-60 and Cs-137 sources, located in the (SSDL) can be utilized. This study aims to determine energy response of a personal thermoluminescence dosimeter (TLD) designed for determining the personal dose-equivalent, $H_p(10)$, in order to investigate whether the calibration curve in the Co-60 gamma field can be utilized for assessing the dose-equivalent in the photon fields with different energies. To do this, first, the TLD dosimeters (an appropriate plastic badge including a TLD-100 chip) are irradiated with a few $H_p(10)$ values using the Co-60 source in the Karaj SSDL. The badges are placed on a water phantom (slab), one meter distant from the source. Then, MCNP4C code is used to calculate the energy response at 662 keV and 1.25 MeV energies. Next, these responses are validated with the experimental data. Finally, the calculation is carried out for several other energies in the range of 20 keV to 1.25 MeV. Obtained results show that for the energies more than 400 keV, The response of the dosimeter is independent of the photon energy, within 10% uncertainty. On the other hand, for the energies smaller than 400 keV, a significant dependence on the energy is observed; such that in 40 keV the response is about 2 times larger than that at 1.25 MeV. Consequently, a method to reduce this uncertainty is needed.

KEYWORDS

Photon energy
Response
TLD
Dose-equivalent

HISTORY

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1 Introduction

After the discovery of the thermoluminescence properties of some materials such as lithium fluoride and their potential for use in radiation dosimetry, a large number of investigations have been carried out on the properties and uses of the dosimeters (Attix, 2008; Morehead Jr and Daniels, 1952; Da Silva et al., 1995; Olko et al., 2006). Various studies have shown that the radiation energy and angle have a significant role in the response of TLD dosimeters. In 1997, Zoetelief and Jansen compared the response of

TLDs loaded in a mouse phantom (Zoetelief and Jansen, 1997). They found that due to the spectral differences caused by attenuation of X-rays, the energy response of LiF TLD differ from the free-in-air value. In 2008, Alves investigated the characterization of a TLD dosimetry system in terms of the stability of the calibration factor obtained in the Cs-137 field (Alves et al., 2008). He also measured the energy response of TLDs on a slab phantom for a few narrow X-ray beams together with Cs-137 and Co-60 gamma rays. He reported an relative energy response from 0.7 to 1.7 in the range of 20 keV to 1.25

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MeV. In another work, Carinou studied the energy dependence of TLD-100 and MCP-N detectors either in air and on a rod phantom (Carinou et al., 2008). In 2013, Banaee and Nedaie evaluated the effect of energy on the calibration of LiF:Mg,Cu,P dosimeters for low and High energy X-rays (Banaee and Nedaie, 2013). They found a maximum deviation of about 25% relative to the response in Co-60 gamma ray energy. Moreover, in 2014 Avila et al. studied the energy dependence of TLD-900 dosimeters exposed to low energy X-rays (Ávila et al., 2014). They used analytical and Monte Carlo methods to obtain the energy dependence and found a maximum deviation of 60% from the Co-60 response in the two methods. Further, in 2016 Herrati et al. investigated the energy response TLD-700 dosimeters to low energy diagnostic X-rays (Herrati et al., 2016). They observed a maximum deviation of 60% in the response of TLDs calibrated in Cs-137 field when using in diagnostic radiology fields. In 2019, Masterson et al. studied the relative response of TLD-100 for measurement of $H_p(3)$ (Masterson et al., 2019). Their work aimed to validate the effect of scattered energy spectra in the accuracy of the eye dosimeters. Finally, in 2022 Benali et al. studied the geometrical effect on the energy response of TLD-100 dosimeters (Benali et al., 2022). They concluded a non-negligible effect of the dosimeter geometry on the energy response for a few radiation beams such as 70 kV X-rays, clinical photon beams of 15 MV and clinical electron beam of 9 MeV.

In the past three years, a thermoluminescence dosimetry system has been established in Nuclear Science and Technology Research Institute (NSTRI) to determine the dose-equivalent of personnel working with the photon fields. One of the largest sources of uncertainty in the dose-equivalent is the energy dependence of the dosimeter. Because, there are only two standard photon sources of Co-60 and Cs-137 located in Karaj (SSDL) available for calibration. When utilizing the calibration curves obtained in these fields for the dosimeters irradiated in the low energy fields, some uncertainty would be imposed on the dose-equivalent values. The reason is the dependency of the dosimeter response on the photon energy leading to the difference of the energy response per unit dose in the measurements field with that in the calibration field. The aim of this work is to determine the energy response of the personal dosimeter used in NSTRI to find out if it is calibrated in the standard fields of Karaj SSDL, the calibration curve can be used for the dosimeters used in the fields with different energies or not.

2 Materials and methods

2.1 Experimental set up

The individual dosimeter used in NSTRI is shown in Fig. 1. In the right and left parts of the figure, the inside and outside views of the badge are shown pointing the filter used for providing 10 mm of tissue. It was a plastic badge equipped with a filter of 1000 mg.cm^{-2} for measurement of HP(10) value. In addition, each badge had a TLD-100 chip as the sensitive volume. In this work, before irradiation

the TLDs were annealed and put in their badges. The irradiation was carried out by means of Cs-137 and Co-60 standard field of Karaj SSDL as shown in Fig. 2 where dosimeters were irradiated with dose-equivalents 0.7, 5 and 20 mSv. These values are chosen from the calibration curve of the TLD dosimeter. 20 mSv is the maximum allowed annual personal dose-equivalent value and 5 mSv is about the limit which is the threshold for taking action in accidents. Also, 0.7 mSv is a typical low dose-equivalent value that may be received by personnel in many radiation activities. The badges were placed on a slab phantom ($30 \text{ cm} \times 30 \text{ cm} \times 15 \text{ cm}$, PMMA walls filled with water) in a 100 cm distance from the source. Before irradiation, the TLD-100 dosimeters were annealed in the oven at $400 \text{ }^\circ\text{C}$ for 1 hours followed by an extra annealing at $100 \text{ }^\circ\text{C}$ for 2 hours. After irradiation in the SSDL, the TLDs were preheated at $100 \text{ }^\circ\text{C}$ for 10 min to eliminate unstable thermoluminescence (TL) signals. Finally, they were read by a Harshaw 4500 TLD reader (Gammasonics, USA) in which the reading procedure started from $50 \text{ }^\circ\text{C}$ to $300 \text{ }^\circ\text{C}$ with a rate $25 \text{ }^\circ\text{C.s}^{-1}$. Furthermore, in the measurements, the total TL response (the electric charge given by the reader) modified by the Elemental Correction Coefficient (ECC) was considered as the desired experimental response.

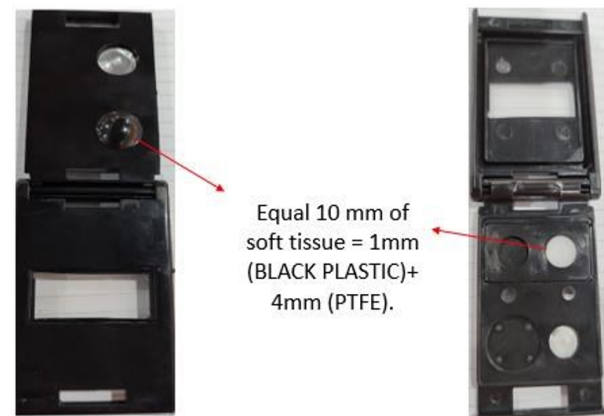


Figure 1: The individual dosimeter used in NSTRI.

2.2 Monte Carlo simulation

In order to calculate the energy response of the individual dosimeter described in the previous section, Monte Carlo simulations using MCNP4C code are performed. The simulated geometry is shown in Fig. 3 in which the badge containing the TLD and the water phantom are considered. Lithium fluoride (LiF) is chosen as the TLD material. To reduce the computation time, the photons are emitted within a solid angle such that at the place of dosimeter on the phantom surface, the field to be a circular plane of 10 cm in diameter. Also, The photon energies from 20 keV to 1.25 MeV were considered. The response at photon energy E is calculated by Eq. (1) (Attix, 2008):

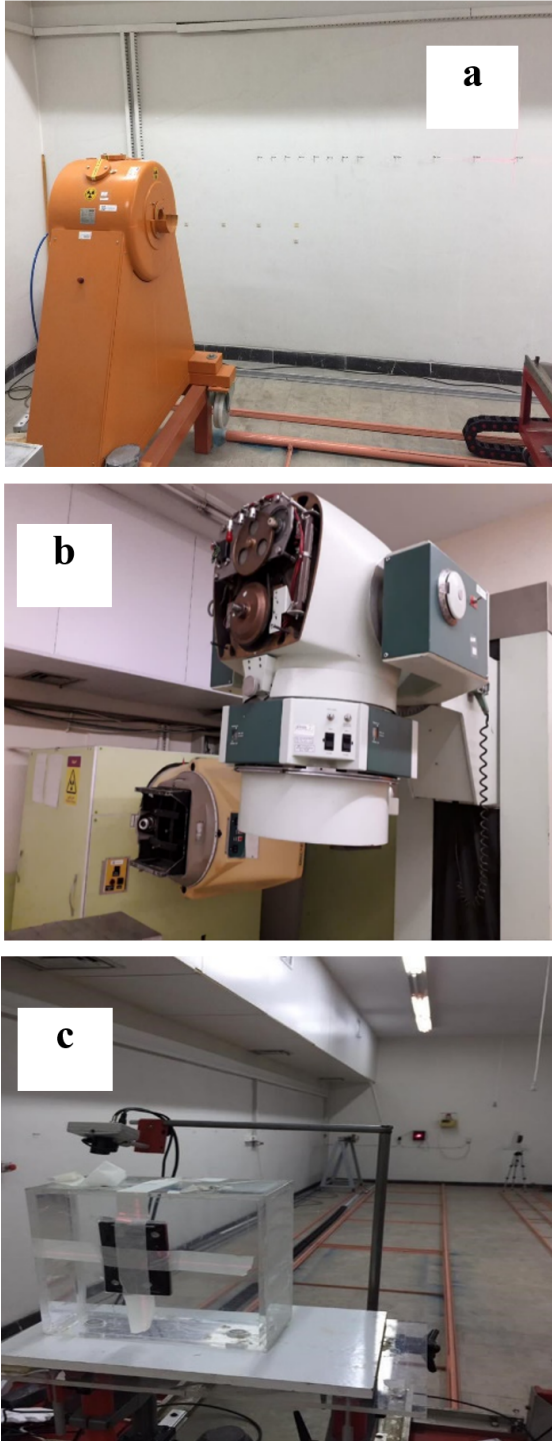


Figure 2: a) The Cs-137 source in Karaj SSDL. b) the Co-60 source embedded in the Picker V9 device in Karaj SSDL. c) The position of TLDs on the phantom.

$$R(E) = \frac{r(E)}{X_{air}(E)} \quad (1)$$

in which $r(E)$ was the reading of dosimeter at energy E and $X_{air}(E)$ is the exposure value at this energy. Since the exposure is proportional to the collision KERMA when charged particle equilibrium (CPE) is established, $K_{c,air}(E)$ was used instead of exposure. Furthermore, Due to the fact that $r(E)$ is proportional to the total energy

deposited in the TLD chip, Eq. (1) changes to

$$R(E) = c \frac{E_{dep}(E)}{K_{c,air}(E)} \quad (2)$$

where c is the proportionality constant. Finally, the relative energy response was obtained by normalizing the response at any energy to that of 1.25 MeV, i.e.,

$$R_{rel}(E) = \frac{R(E)}{R(1.25 \text{ MeV})} \quad (3)$$

The energy deposit and air KERMA values were calculated by *F8 tally in the TLD and F6 tally in the air, respectively. To obtain the air KERMA, an air sphere with 5 cm diameter was simulated instead of the dosimeter without phantom. It should be notified that to have CPE condition, a PMMA wall was considered surrounding the air sphere. For any energy, the thickness of PMMA wall was selected equal to the range of secondary electrons with energies equal to their primary photons obtained from the NIST library (Berger et al., 2017). Table 1 presents the CSDA range of electrons in air and PMMA.

In order to validate the simulation, first the energy responses of 662 keV and 1.25 MeV gamma rays together with the relative responses (to 1.25 MeV) were calculated. The responses were computed per unit of dose-equivalent. Then, the experimental relative responses were determined from the TL responses (i.e., the charge measured by the reader in the unit of nC) measured for three dose-equivalents of 0.7, 5 and 20 mSv. It should be noted that for any dosimeter, the TL response was multiplied by the corresponding ECC value of the TLD chip. Next, the average relative response was compared with the calculated one.

Table 1: The CSDA ranges obtained from the NIST library (Berger et al., 2017).

E (MeV)	CSDA range (cm) in air	CSDA range (cm) in PMMA
0.020	0.8	0.001
0.040	2.7	0.002
0.060	5.6	0.005
0.080	9.3	0.008
0.100	13.5	0.012
0.140	26.6	0.024
0.300	79.3	0.073
0.400	121.3	0.111
0.511	165.8	0.152
0.662	248.3	0.228
0.800	310.0	0.285
1.000	409.2	0.378
1.250	595.8	0.554

3 Results and discussion

Table 2 presents the calculated and experimental relative responses. The uncertainty value (with coverage factor of 2) of the measured responses is 25% in the used TLD dosimetry system which is added to the table. The comparison reveals that for the both energies considered (662

Table 2: The experimental values of the relative energy response for the dosimeters irradiated with dose-equivalents 0.7, 5.0, and 20.0 mSv. Two standard deviations of the data are presented.

$H_p(10)$ (mSv)	$R_{TL,exp}$ (nC)	$R_{rel,exp}$	$R_{rel,exp,ave}$	R_{cal}	$R_{rel,cal}$
0.7	Cs: 255.81 ± 63.98	0.91 ± 0.32			
	Co: 282.31 ± 70.58				
5.0	Cs: 2083.56 ± 520.90	1.06 ± 0.37	1.00 ± 0.58	Cs: 1.00 ± 0.02	1.00 ± 0.03
	Co: 1964.42 ± 491.1				
20.0	Cs: 8362.41 ± 2090.60	1.03 ± 0.36			
	Co: 8062.89 ± 2015.62				

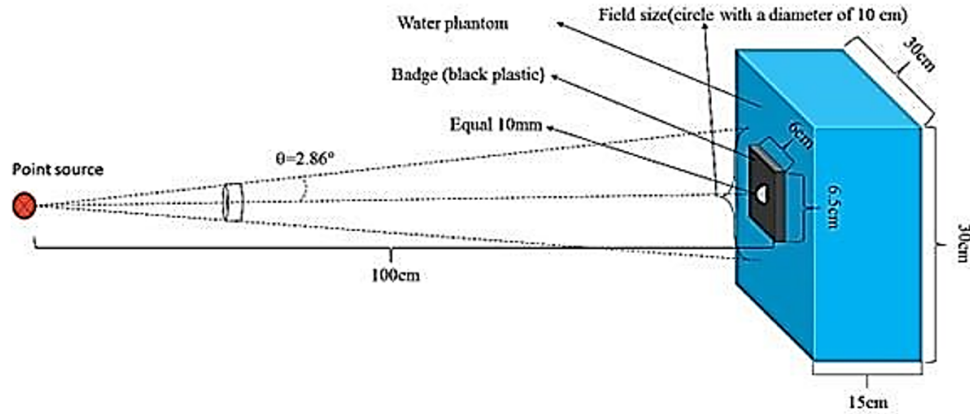


Figure 3: The geometry simulated using the MCNP4C code.

keV and 1.25 MeV), the calculated and experimental relative responses are the same (both equal to 1.00). Therefore, the simulation is confirmed by the experimental data.

After validation of the simulation, the energy responses for other energies are computed by Eq. (3) as given in Table 3. The uncertainty values (coverage factor of 2) are determined using the error propagation formula. Furthermore, Fig. 4 shows the variation of relative energy response vs. the photon energy. The calculated and experimental values are included in the figure. The error bars show the standard deviation of the data. As can be observed, the curve has a peak below 0.4 MeV where the relative energy response reaches to its maximum value (=1.92) at 40 keV. In this energy range, the photoelectric effect dominates where the absorption coefficients of the dosimeter (including the badge and TLD) are vastly different from that of air. On the other hand, for the energies larger than 0.4 MeV, the response is almost independent of photon energy. Because, in this region Compton scattering is the dominant interaction where the absorption coefficients of the dosimeter and the air are similar. This result can be compared with the work of Alves [6] who has reported a relative energy response of TLDs between 0.7 and 1.7 in the range 20 keV to 1.25 MeV. Similarly in his work, the maximum deviation from the response at Cs-137 gamma ray energy occurs in the low energy region.

As the final point, regarding Fig. 4 and Table 3, one can conclude that for the individual dosimeter using TLD-100 chip some correction is required for the energy response, especially for the energies smaller than 0.4 MeV. The reason is that the calibration carried out in Cs-137 or

Co-60 fields can be used for the other energies only when the dosimeter response is independent of the photon energy. Otherwise, there would be some error in determining the dose-equivalent especially in the low energy region. Considering the single photon energies, the required correction factors can be defined as the inverse of the relative response values. Table 4 presents the correction factors for different photon energies considered in this work. It is found that their variation with the photon energy is the inverse of that of for the relative responses plotted in Fig. 4.

Table 3: Calculated values of the energy response for different photon energies.

E (MeV)	K_{air} (J.Kg ⁻¹)	E_{dep} (MeV)	$R(E)$	R_{rel}
0.02	1.01E-17	1.08E-09	1.07E+08	0.85±0.04
0.03	4.46E-18	8.99E-10	2.02E+08	1.61±0.06
0.04	2.73E-18	6.58E-10	2.41E+08	1.92±0.04
0.06	2.01E-18	4.63E-10	2.31E+08	1.84±0.08
0.08	2.28E-18	4.39E-10	1.93E+08	1.54±0.06
0.10	2.84E-18	4.89E-10	1.72E+08	1.37±0.02
0.14	4.29E-18	6.72E-10	1.57E+08	1.25±0.02
0.30	1.09E-17	1.43E-09	1.32E+08	1.05±0.04
0.40	1.49E-17	1.89E-09	1.27E+08	1.01±0.04
0.511	1.91E-17	2.41E-09	1.27E+08	1.01±0.04
0.662	2.44E-17	3.05E-09	1.25E+08	1.00±0.02
0.80	2.90E-17	3.60E-09	1.24E+08	0.99±0.04
1.00	3.51E-17	4.28E-09	1.22E+08	0.97±0.04
1.25	4.17E-17	5.23E-09	1.26E+08	1.00±0.02

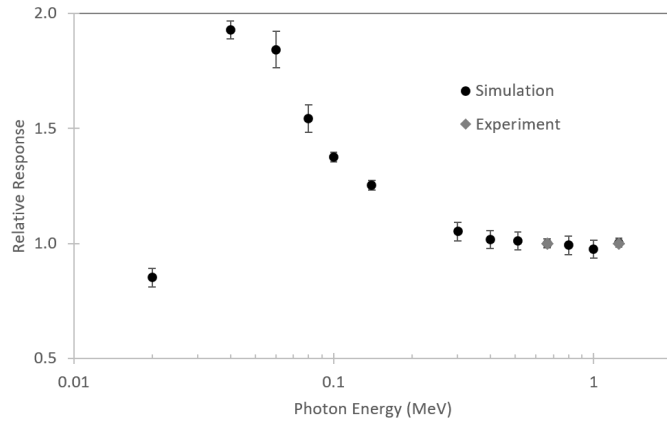


Figure 4: Variation of the calculated relative energy response of the individual dosimeter vs. photon energy. The experimental values at 662 keV and 1.25 MeV are also included. Error bars show the uncertainty values with the coverage factor of 2.

Table 4: The correction factors to be applied for the relative response.

E (MeV)	R_{rel}	Correction factor
0.02	0.85 ± 0.04	1.17
0.03	1.61 ± 0.06	0.62
0.04	1.92 ± 0.04	0.52
0.06	1.84 ± 0.08	0.54
0.08	1.54 ± 0.06	0.65
0.10	1.37 ± 0.02	0.73
0.14	1.25 ± 0.02	0.80
0.30	1.05 ± 0.04	0.95
0.40	1.01 ± 0.04	0.98
0.511	1.01 ± 0.04	0.99
0.662	1.00 ± 0.02	1.00
0.80	0.99 ± 0.04	1.01
1.00	0.97 ± 0.04	1.03
1.25	1.00 ± 0.02	1.00

4 Conclusions

In the present work, the energy response of personal dosimeter based on the TLD-100 chip is calculated in the energy range of 20 keV to 1.25 MeV using the MCNP4C code. The results for 662 keV and 1.25 MeV is validated by the measurements. It is found that there is dependency on the photon energy in the low energy region (below 400 keV). As a result, in order to use the calibration curve obtained in the Cs-137 or Cs-60 in the Karaj SSDL (as the only standard fields in the country) for the dosimeters irradiated in the low energy fields, some correction factors are required to obtain the dose-equivalent values with less uncertainty. The correction factors vary inversely with the relative energy response.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

References

- Alves, J. G., Calado, A. M., Cardoso, J. V., et al. (2008). Energy and angular dependence of the personal dosimeter in use at ITN-DPRSN. *Radiation Measurements*, 43(2-6):641–645.
- Attix, F. H. (2008). *Introduction to radiological physics and radiation dosimetry*. John Wiley & Sons.
- Ávila, O., Ramírez-Barbosa, E., and Gamboa-deBuen, I. (2014). Energy dependence of TLD-900 dosimeters exposed to low energy X-rays. *Radiation Measurements*, 71:127–132.
- Banaee, N. and Nedaie, H. (2013). Evaluating the effect of energy on calibration of thermo-luminescent dosimeters 7-LiF: Mg, Cu, P (GR-207A). *International Journal of Radiation Research*, 11(1):51.
- Benali, A., Ishak-Boushaki, G. M., Riffaud, J., et al. (2022). Geometrical effects on luminescent dosimeter energy response. *Journal of Instrumentation*, 17(01):P01035.
- Berger, M., Coursey, J., Zucker, M., et al. (2017). Stopping-power and range tables for electrons. *Protons, and Helium Ions*.
- Carinou, E., Boziari, A., Askounis, P., et al. (2008). Energy dependence of TLD 100 and MCP-N detectors. *Radiation Measurements*, 43(2-6):599–602.
- Da Silva, T., Da Rosa, L., and Campos, L. (1995). Thermo-luminescence dosimeter for personal dose equivalent assessment. *Radiation Protection Dosimetry*, 58(1):17–21.
- Herrati, A., Bourouina, M., and Khalal-Kouache, K. (2016). Investigation of TLD-700 energy response to low energy x-ray encountered in diagnostic radiology. *Open Physics*, 14(1):150–158.
- Masterson, M., Cournane, S., McWilliams, N., et al. (2019). Relative response of dosimeters to variations in scattered X-ray energy spectra encountered in interventional radiology. *Physica Medica*, 67:141–147.
- Morehead Jr, F. F. and Daniels, F. (1952). Storage of radiation energy in crystalline lithium fluoride and metamict minerals. *The Journal of Physical Chemistry*, 56(5):546–548.
- Olko, P., Currivan, L., Van Dijk, J., et al. (2006). Thermoluminescent detectors applied in individual monitoring of radiation workers in Europea review based on the EURADOS questionnaire. *Radiation Protection Dosimetry*, 120(1-4):298–302.
- Zoetelief, J. and Jansen, J. T. M. (1997). Calculated energy response correction factors for LiF thermoluminescent dosimeters employed in the seventh EULEP dosimetry inter-comparison. *Physics in Medicine & Biology*, 42(8):1491.

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