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A Validation Study on Radiation Properties of a Novel LiF: Mg, Ti Known as IAP-100

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ABSTRACT

Introduction: LiF dosimeter has the most application in medicine. This study aimed to evaluate some dosimetric properties of a novel LiF: Mg, Ti.
Materials and Methods: An ELEKTA Precise linear accelerator was used to calibrate dosimeters at 6 MV. In this survey, responses of dosimeters were evaluated up to 1000 cGy. Background effect was investigated in two different dosimeter states including irradiated and unirradiated. Thermoluminescence response dependence to dose rate was investigated, as well. Energy dependence was evaluated in diagnostic and therapeutic ranges. Furthermore, fading effect was evaluated by reading the dosimeters every 2 h up to 12 h post-irradiation.
Results: The dosimeters had linear response up to 250 cGy. Readout values of dosimeters receiving 120 cGy at three dose rates of 21, 212, 425 cGy.min^{-1} were calculated equal to 125, 123, 121 cGy, respectively. The measured values of delivering 80, 120, and 150 cGy prescribed doses at 6 MV, 10 MV, and 15 MV were accurate at 6 MV and about 1.5 times higher than the prescribed doses at 10 and 15 MV. Thermoluminescence response in diagnostic energy range showed an uprising trend with increasing energy.
Conclusion: The raising thermoluminescence response with increasing energy contradicts with the findings of Nunn. Due to the reproducibility and linear response of dosimeters in an acceptable dose range, they could be used in diagnostic and therapeutic fields. Effects of absorbed doses from background in low-dose studies, mainly in diagnostic radiology range, could be evaluated in more detail in future surveys.

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Introduction

Thermoluminescence dosimeters (TLDs) are one of the most practical instruments used in measuring absorbed dose, which are used in various dosimetric surveys such as quality assurance of therapeutic systems, measurement of the delivered dose to treated organs by in vivo dosimetry, and personnel dosimetry in diagnostic procedures [1]. TLDs are available in powder, cubic, and chips forms and are composed of various components. Each of these TLD types has special characteristics such as response linearity in an acceptable dose range and independence of response from energy and dose rate. The LiF dosimeter family has the most application in medicine. Three common dosimeters of this group include TLD-100, TLD-600, and TLD-700, which contain 92.5% ^{7}Li plus 7.5% ^{6}Li, 96.5% ^{6}Li plus 4.4% ^{7}Li, and 99.99% ^{7}Li plus 0.01% ^{6}Li, respectively. Impurities contained in these dosimeters, including magnesium and titanium, increase electron traps, hence enhanced dosimeter sensitivity. Effective atomic number of the dosimeter (8.14) is nearly similar to those of the body tissues (7.4) [2].

Among the dosimeters mentioned above, TLD-100, which is almost made in chips form, is more available and easier to use in medicine [3]. Various types of TLD-100 show different behaviors in response to megavoltage photon irradiation [4]. This study sought to evaluate some dosimetric properties of a novel Iranian LiF: Mg, Ti, known as IAP-100, which is produced in dimensions of 3.2 × 3.2 × 0.9 mm^3. Twenty-one of these white colored chips were prepared and evaluated. It should be noted that all the stages of this survey were performed with an ELEKTA Precise at 6 MV energy beam, unless the use of any other system or energy range is mentioned.

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Materials and Methods

Calibration

An ELEKTA Precise™ (ELEKTA, Sweden) linear accelerator was used to calibrate the dosimeters at 6 MV. Firstly, a dose of 1 Gy was delivered to the dosimeters to perform the first stage of calibration. The first Element Correction Coefficient (ECC) was calculated and recorded by Harshaw™ 3500 Reader (Harshaw Chemical Company, Solon, OH) for each dosimeter. To determine the first stage ECC, the 10% limit for each of the dosimeters was determined, so that if there is a difference of more than 10% between each dosimeter's response and the average, it will be excluded from the study process. Following the calculation of the second ECC, the Reader Calibration Factor (RCF) was calculated by delivering the prescribed dose of 49 cGy. Then, all the calibration dosimeters that met the defined criteria by the software were selected as field dosimeters and the following evaluations were performed on them.

Readout and Annealing

The dosimeters were read at 24 to 48 h post-irradiation; readout of each dosimeter took almost 30 s. Before the onset of the main reading, temperature of the dosimeters was raised to 150°C in 10s during the preheat phase in order for depletion of low energy signals [5]. Then, at the first 15 s of the readout time, the temperature was increased to 300°C at the heating rate of 10°C/s. During the last 15 s of the readout phase, temperature remained steady until the completion of the readout phase and drawing the glow curve of the dosimeter by the reader software.

Figure 11 represents a summary of what has been described about the reading process. In fact, the figure shows a glow curve of a dosimeter that was readout individually. The glow curve's left vertical axis shows thermoluminescence response in the form of electrical intensity, the right vertical axis demonstrates the dosimeter's temperature, and the horizontal axis indicates the channels of dosimetry in which the information of each individual dosimeter is recorded. Annealing of the dosimeters was performed as follows; 1 h heating in an electric oven at 400°C, then cooling down to room temperature for 10 min and heating in another electric oven at 100°C for 2 h. Ultimately, the residual signals of radiation were removed and the dosimeters were prepared for the next irradiation.

Evaluation of linearity and supralinearity

After completion of the calibration stage and converting the calibration dosimeters to field dosimeters, the dosimeters were prepared to evaluate their dose response. For this purpose, some doses, each one in two stages, were delivered to three dosimeters. Every stage of irradiation was replicated. Thus, each dose value was delivered to six dosimeters. The dosimeters' responses were evaluated up to 10 Gy. The doses delivered to the dosimeters were 10, 20, 50, 80, 100, 120, 150, 170, 185, 200, 220, 235, 240, 250, 260, 300, 400, 500, 600, 700, 800, 900, and 1000 cGy. The thermoluminescence response curve could be drawn in terms of reference dose. Different regions of the chart could be cleaved to linear, supralinear, and saturated [6].

Background Effect

Background effect is considered to be significant in low-level dosimetry, such as in occupational measurements [7]. In this survey, the background effect was investigated in two different states of dosimeters, that is, irradiated and unirradiated. In the former state, assessment of the effect of measured values from the background was investigated as follows, dose values of 90, 200, 800, 1000, 1200, 1500, and 1700 mGy were delivered to dosimeters; in this state, the doses were delivered to the dosimeters in two manners. Firstly, the dose values were delivered to dosimeters one day after the last annealing. The results of this manner were compared with the other one in which the same doses were delivered two weeks following the last annealing. This part of the study was carried out to clarify the effect of background irradiation on irradiated dosimeters up to two weeks.

For the latter state, the effect of background irradiation on unirradiated dosimeters was evaluated by reading them at three main times, including immediately, 12 days, and three months post-annealing. In addition, the readout values of the three mentioned time points were compared with the values of reading with no TLD on planchette.

Dose Rate Effect

The dose rate effect on thermoluminescence response was investigated in several studies, including studies in which the air kerma rate was mentioned as an effective factor on thermoluminescence response [8-10]. In this survey, to evaluate the thermoluminescence response dependence on dose rate, some dose values were delivered to dosimeters at the three dose rates of 21, 211, and 425 $cGy.min^{-1}$. For the 21 $cGy.min^{-1}$ dose rate, 106 cGy was firstly delivered to three dosimeters; then, 106 plus 14 cGy as the fractionated dose was delivered to four other dosimeters to evaluate the possible effect of dose fractionation on responses. For assessing the thermoluminescence response at two other dose rates, a single dose of 120 cGy was delivered to seven dosimeters.

Energy Response

Energy dependence of TLD is considered to be important since most of ionizing radiation fields, especially photon fields, consist of energy spectrum, and the thermoluminescence response varies with different energies and spectrums [3]. In this survey, energy dependence was evaluated in both megavoltage and kilovoltage energy ranges. In the megavoltage range, the doses of 80, 120, and 150 cGy were delivered to the dosimeters at 10 MV and 15 MV. Thereafter, the results were compared with those of the same prescribed dose values at 6 MV, in which the calibration was performed.

The response of dosimeters in kilovoltage energy range was evaluated using a diagnostic radiology unite. Further, a RadCal dosimeter with a 6-mm^3 chamber volume was employed as the reference dosimeter. Exposures were provided at energy values of 40-100 kV by step 10 kV, with mAs equal to 100 for each energy.

Post Irradiation Readout Time and Fading

Fading is an important property of TLDs, which should be surveyed for evaluating signal maintenance during time at a specified temperature. Fading increases significantly as time passes and temperature rises. This effect is mainly due to moving electrons from low energy levels to sustainable levels. The luminance curves obtained from the dosimeter readings at different times must be in conformity with each other [5, 11]. In this study, the fading effect of low energy signals was evaluated for a few hours. The main purpose of this section of the study was to achieve an optimum time for reading after irradiation. This optimum time was chosen based on the lowest standard deviation and shortness time.

In order to obtain an optimal minimum reading time after irradiation, 120 cGy was delivered to each dosimeter, and then the readout process was carried out every 2 h until 12 h and 24 h post-irradiation. The mean and standard deviations of the readout values were calculated for each readout process.

Results

Calibration

At the first calibration stage, the first ECC was calculated for each dosimeter by determining 10% of tolerance from average for each dosimeter. Thermoluminescence response of all the dosimeters with 10% of tolerance level was within the acceptable range. Such that all the calibration dosimeters were selected as field dosimeters. The Reader Calibration Factor was calculated equivalent to 0.00388946 µC.mGy^{-1}. The maximum standard deviation of the dosimeter responses was 0.18 in the calibration phase.

Linear and Supralinear Region

Dosimeters had a linear response up to 250 cGy. Then, they slowly began to get out of their linear range. At higher doses, supralinearity behavior was observed in dosimeter responses. Figure 1 exhibits the thermoluminescence responses up to 260 cGy. Figure 2 shows a dose-response curve, but the curve is plotted up to 10 Gy. In Figure 3, the prescribed doses were compared with the measured ones, indicating that the highest standard deviation was 15.3 for the dose of 10 Gy. By irradiation up to 10 Gy, the saturated region of the thermoluminescence response curve was not reached.

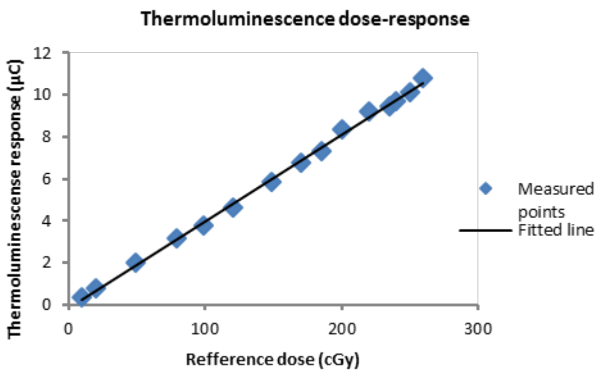

Figure 1. Linear region of dose-response curve; the plot represents the reference dose (cGy) versus thermoluminescence response (µC) of the dosimeters irradiated at 6 MV.

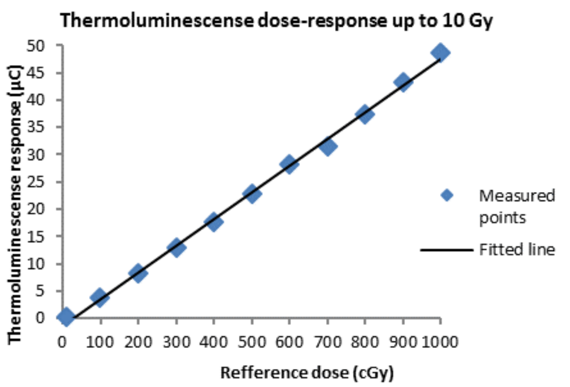

Figure 2. Thermoluminescence dose-response up to 10 Gy, irradiated at 6 MV

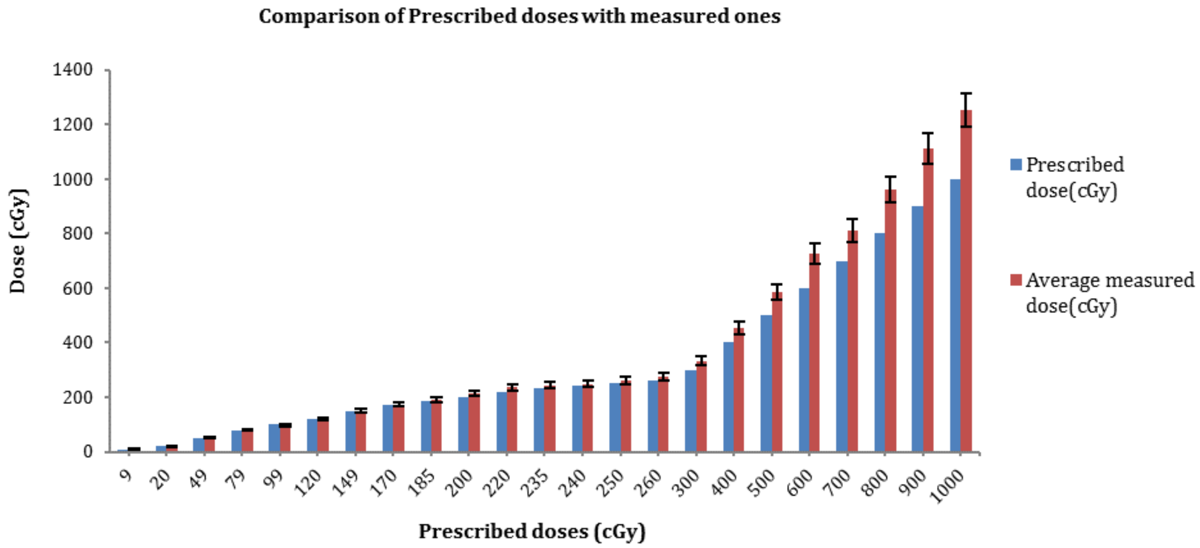

Figure 3. Comparison of the prescribed doses with the measured ones; various prescribed doses are delivered at 6 MV. Higher standard deviations are observed at higher doses according to the error bars.

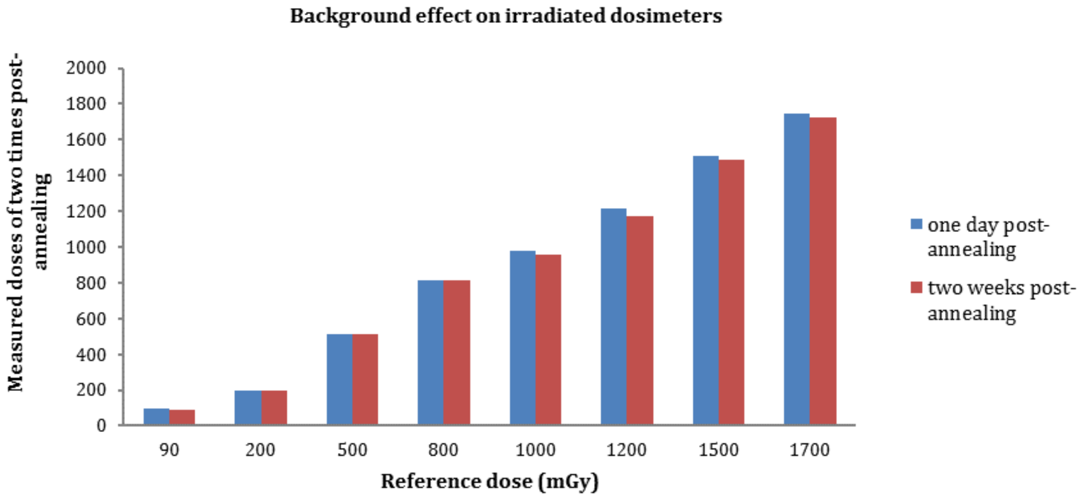

Figure 4. Background effect on irradiated dosimeters at the specified doses delivered at 6 MV. It can be observed that two groups of dosimeters irradiated one day and two weeks post-annealing had similar responses.

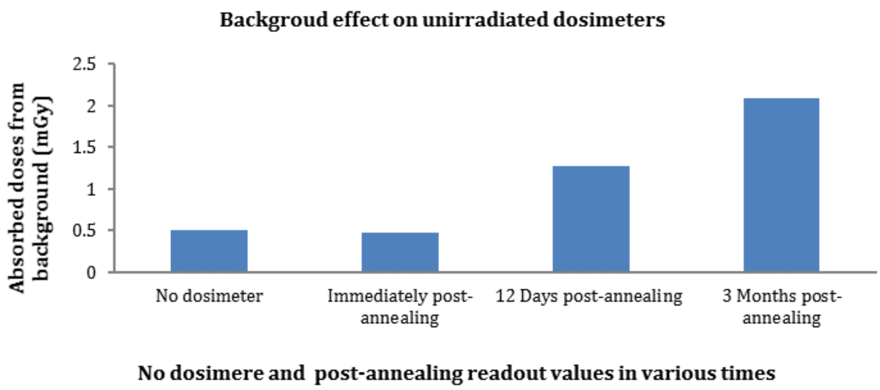

Figure 5. Background effect on unirradiated dosimeters; difference of absorbed doses at various time intervals post-annealing of unirradiated dosimeters and readout results with no Thermoluminescence dosimeters on planchette are shown.

Background Effect

As shown in Figure 4, passing one day from annealing the dosimeters did not lead to a significant difference in the readout values compared to the ones irradiated two weeks post-annealing. In all the cases, the measured dose values in the first state (irradiated one day post-annealing) were higher than in the second one (irradiated two weeks post-annealing). Figure 5 represents the background effect on the unirradiated dosimeters. As shown in the figure, in addition to the three main plots of measurement, which were readout immediately, 12 days, and 3 months post-annealing, the first plot (on the left side of the figure) refers to readout procedure with no TLD on the planchette. The measured values were equal to 0.49, 0.47, 1.27, and 2.08 mGy from left to right of the figure. Higher readout values with no TLD on the planchette were observed comparing ones immediately were readout with TLDs on planchette post-annealing.

Dose Rate Effect

By delivering 120 cGy at the three dose rates of 21, 212, and 425 cGy.min^{-1}, the measured doses were calculated as 125, 123, and 121 cGy, respectively. The results are presented in Figure 6. As shown in the figure, with increasing the dose rate, the measured values decrease. In addition, dose fractionation had no effect on the average measured values.

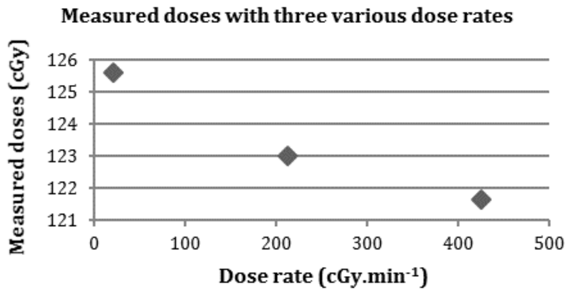

Figure 6. The effect of increasing the dose rate on measured doses of dosimeters that received 120 cGy at 6MV; as shown, by increasing dose rate, the measured values of dosimeters decreased.

Energy Effect on Thermoluminescence Response

Energy dependence was evaluated in both diagnostic and therapeutic ranges. Energy dependence of thermoluminescence response of dosimeters in megavoltage range was evaluated at 6 MV, which calibration was performed, and also at 10 MV and 15 MV energy values (Figure 7). As shown in the figure, the readout values for the dosimeters that received the 80 cGy prescribed dose were respectively 80.73, 124.7, and 118.71 for the three energies 6 MV, 10 MV and 15 MV. The same readout values for the 120 cGy prescribed dose were 119, 181.65, and 181.75, respectively, and for the 150 cGy prescribed dose, the results were 150, 229.6, and 231.46 cGy, respectively.

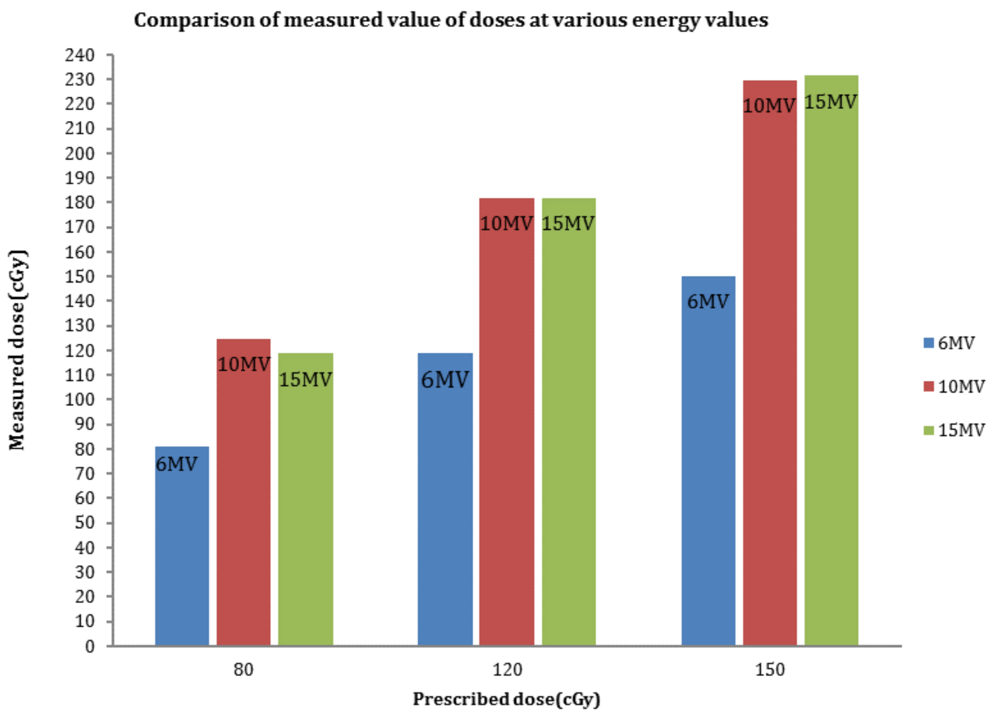

Figure 7. Comparison of the prescribed doses with the measured doses relative to 6 MV photon beam. The comparison at each prescribed dose is performed between the prescribed doses delivered at all the three energy values

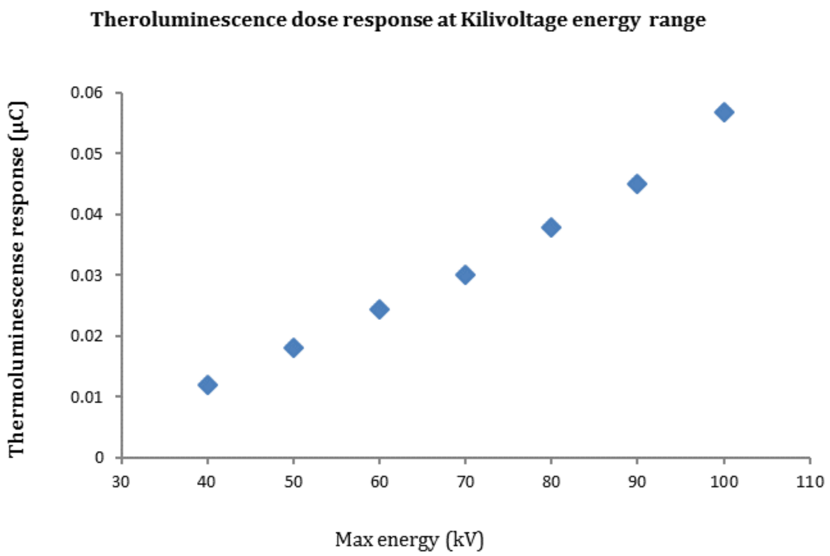

Figure 8. Thermoluminescence dose response relative to 6 MV by increasing energy, with constant mAs equal to 100. The upward trend of thermoluminescence response can be observed.

Table 1. Reference dose and measured doses in kilovoltage energies; ratios are shown in the last column

Energy	Ref. dose (mGy)	Meas. dose(mGy)	Ratio
40	0.796	3.097667	3.891541
50	1.56	4.628667	2.967094
60	2.444	6.287333	2.572559
70	3.419	7.742667	2.2646
80	4.497	9.721	2.161663
90	5.684	11.58333	2.037884
100	6.954	14.62333	2.102866

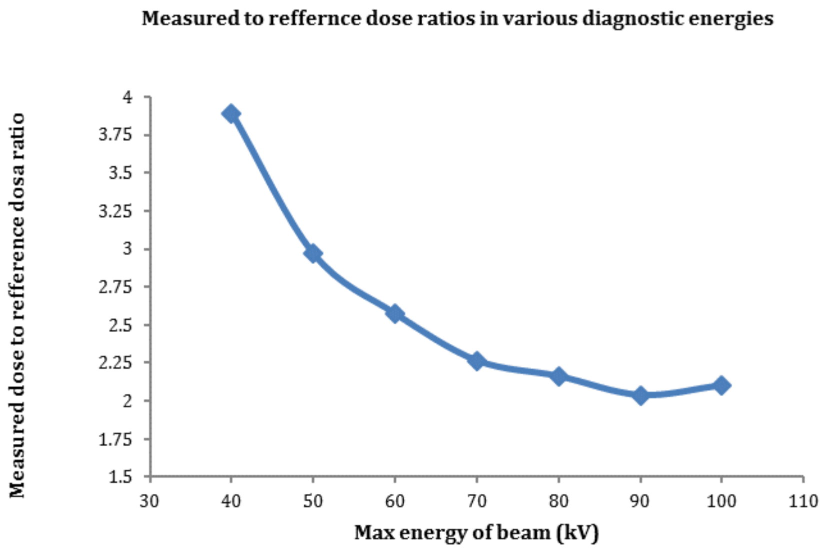

Figure 9. Representation of the gradual reduction in measured dose to reference dose ratio with increasing energy

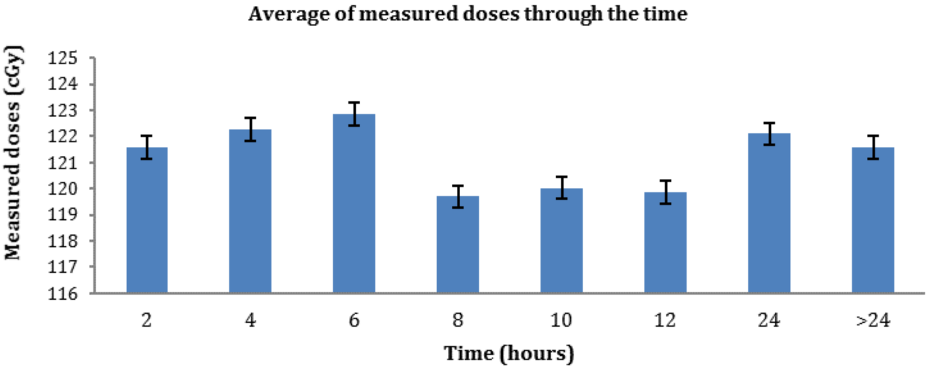

Figure 10. Investigation of fading effect by reading the irradiated dosimeters, which received 120 cGy at 6 MV

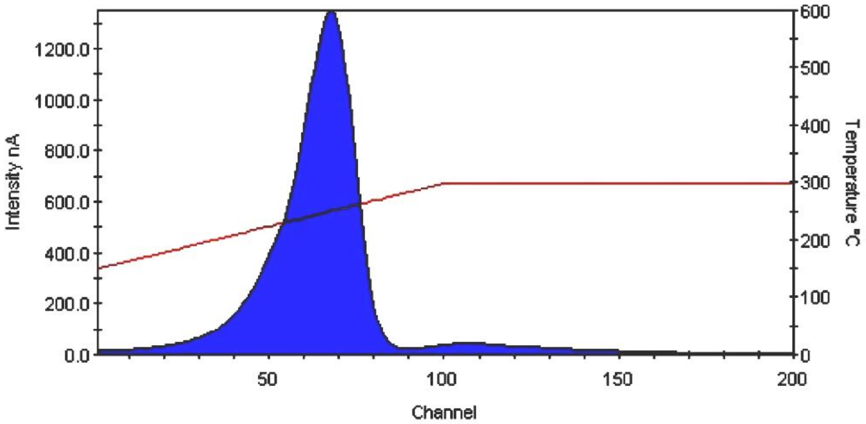

Figure 11. Sample glow curve of a dosimeter readout 12 hours after receiving a 120 cGy dose

Figure 8 demonstrates the relationship between thermoluminescence response and beam energy in the kilovoltage range. In the figure, the measured points represent the thermoluminescence response of TLDs relative to 6 MV as a function of energy values. The figure marks an increase in thermoluminescence response by enhancing energy. Further, energy response in kilovoltage range was evaluated by comparing readouts to reference dose value ratios for each of energies. The results of this section of the study are provided in Table 1. Figure 9 pinpoints the downward trend of this ratio with increasing energy. The descending trend continues up to 90 kV. The figure is plotted based on the results of Table 1. Ideally, the measured to reference dose value ratio must be equal to one for each energy. The maximum amount of this ratio pertains to the 40 kV, which was calculated equivalent to 3.89.

Readout Time Post-Irradiation

After irradiation, the reading process was carried out every 2 h up to 12 h. Figure 10 represents the average of readout values at 2-h intervals. In addition, no considerable change was observed in the dosimeters' glow curves. Based on the results, 12 h post-irradiation is the optimum readout time. Figure 11 displays a sample glow curve of a dosimeter that was readout 12 h post-irradiation.

Discussion

The results of the present study can be considered a good source for the future measurements using this type of TLD. Comparison of the results of linearity of this dosimeter with those of a study which performed by the International Atomic Energy Agency (IAEA) in 2013 showed that the present dosimeter has a linear response up to 250 cGy, while the TLD-100 studied by the agency had a linear response up to 100 cGy [11]. In the study by the agency, an exact time to readout the dosimeters post-radiation was not mentioned, while it is possible to suggest an optimum time based on the average readout values of the doses and standard deviations of the average readout values. The optimum readout time minimizes the effect of low-energy signals on the readout values. It can be noted in Figure 5 that the average readout values with no dosimeters on planchette were higher than the measured values of the dosimeters that had been annealed recently. This effect could be referred to as reader noise and is considered to be statistically insignificant. Furthermore, in subsequent evaluations, background effect on unirradiated dosimeters could be assessed more accurately by reading annealed dosimeters at more various times post-annealing. This will render more details about lower level detection of the dosimeters, which seems to be important in low-level dosimetry. However, the results of this survey showed a 1.27 mGy value of the lower level of detection 12 days post-annealing.

Energy response of the dosimeter in the megavoltage range were similar at 10 and 15 MV energy values, such that based on the results of Figure 7, the measured doses at 10 and 15 MV should be divided by 1.5 in order to convert them to real absorbed doses. Considering the downward trend of measured to reference dose ratios (shown in table 1 and figure 9) with increasing energy in kilovoltage range, a similar action could be taken for estimating the real absorbed dose; based on the results of Table 1, absorbed doses could be estimated by dividing the readout value by the ratio calculated at each energy. The observed dose responses in kilovoltage range are shown in Figure 8, which needs further etiological investigations since the increasing thermoluminescence response with increasing energy contradicts the results of a study performed by Nunn in 2008 [12]. In the mentioned study, a decreasing trend in thermoluminescence response relative to 60Co was observed by increasing energy in the same energy range as the present study.

Wrobel et al. in 2006 studied the thermoluminescence response of a chemical vapor at various air kerma rates. The results of the mentioned study revealed high variations by altering the air kerma rate, such that the signals increased by decreasing the air kerma rate up to a specific point of measurement [9]. This could be considered as a disadvantage for thermoluminescence materials. In addition, in our study, the measured doses reflected a descending trend with increasing dose rate. Nonetheless, the observed changes due to the increasing dose rate were not as high as those of the study by Wrobel.

Choosing an optimum TLD readout time is considered an important issue for the accuracy of thermoluminescence response. In this study, an optimum readout time was suggested by evaluating the fading effect of TLDs through reading their responses every 2 h up to 12 h post-irradiation. Regarding 119.86 cGy of the measured value and the standard deviation of 0.95 for the dosimeters receiving 120 cGy, 12 h after irradiation was suggested as an optimum post-irradiation time. However, changes of other average readout values shown in Figure 10 were statistically insignificant. The readout time suggestion was based on the comparison drawn between the average readout values and the standard deviations as shown in Figure 10.

Considering the limited number of dosimeters, various parts of this survey, based on requirement, were repeated several times, which showed an acceptable reproducibility of the TLDs.

Conclusion

In this survey, various characteristics of a newly produced TLD, which is similar to TLD-100, were evaluated. The dosimeter shows a linear response up to 250 cGy. Going beyond the mentioned dose range presents a gradual supralinear response. In subsequent studies, the saturated region of the dose-response curve could be evaluated by delivering doses beyond 10 Gy. As noted in the results, a difference was observed between the measured values of dosimeters that received equal doses immediately and two weeks post-annealing; however, the difference was insignificant.

The effect of absorbed doses from background on low-dose studies, mainly in the diagnostic radiology range, could be evaluated in the future studies. In other words, since the lower detection limit in the survey was evaluated only immediately and 12 days post-annealing, this characteristic could be evaluated more accurately in subsequent studies. Maximum standard deviation of 0.18 in the calibration phase shows an acceptable reproducibility. Regarding the high reproducibility and linear response of the dosimeter in an acceptable dose range, this dosimeter could be used in different diagnostic and therapeutic aspects of dosimetry, especially in personnel dosimetry.

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