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Characterization and Correction of Fading Effects in GeDOFs Microdosimeter for Absorbed Dose Measurements

(Pencirian dan Pembetulan Kesan Pudar dalam Mikrodosimeter GeDOFs untuk Pengukuran Dos Serap)

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ABSTRACT

This study investigates the thermoluminescence (TL) fading of fabricated germanium-doped optical fibers (GeDOFs) with a focus on TL signal intensity, glow curve, best-fit curve, and correction factor. Two distinct GeDOFs geometries, cylindrical fiber (CF) and flat fiber (FF), were compared for TL intensity decay under 6 MV and 10 MV photon beams. TL intensity measurements were recorded from the first day post-irradiation to the 106th day and a comparison of two fading curve-fitting approaches was carried out. Fading correction factor (K_{fad}) was derived, and the corresponding uncertainties were calculated. Over time, GeDOFs exhibited a decline in TL intensity, with a notably rapid decay occurring in the initial 30 days after irradiation. The most substantial TL intensity loss was observed in FF, with values of 58.9% for 6 MV and 63.4% for 10 MV. The evaluation of curve fitting showed that the best conformity was achieved through a single exponential decay equation model. The area under the glow curve decreased as the time between GeDOFs irradiation and TL readout increased. K_{fad} was determined by comparing the fading function of reference GeDOFs to that of the measured ones. The estimated uncertainties associated with K_{fad} were found to be 0.06% for CF and 0.12% for FF, respectively. GeDOFs exhibit fading characteristics influenced by TL readout interval time and radiation energy. When quantifying the absorbed dose from photon beams, it is crucial to account for the fading correction factor to ensure the precise and accurate measurement of the dose.

Keywords: Correction factor; dosimetry audit; fading; Ge-doped optical fibres

ABSTRAK

Kajian ini meneliti kemerosotan termopendarcahaya (TL) gentian optik dop Ge yang difabrikasi (GeDOFs) dengan tumpuan diberikan kepada keamatan isyarat TL, lengkungan bara, lengkungan padanan terbaik dan faktor pembetulan. Dua geometri GeDOFs yang berbeza, gentian silinder (CF) dan gentian leper (FF) dibandingkan tahap kemerosotan keamatan TL di bawah sinaran foton 6 MV dan 10 MV. Pengukuran keamatan TL direkodkan dari hari pertama selepas penyinaran hingga hari ke-106 dan perbandingan antara dua pendekatan padanan lengkungan kemerosotan telah dijalankan. Faktor pembetulan kemerosotan signal (K_{fad}) diterbitkan dan ketidakpastian yang berkaitan telah dihitung. Seiring berjalannya masa, GeDOFs menunjukkan penurunan keamatan TL dengan kemerosotan yang ketara berlaku dalam tempoh 30 hari pertama selepas penyinaran. Kehilangan keamatan TL yang paling ketara diperhatikan pada FF, dengan nilai pengurangan sebanyak 58.9% untuk 6 MV dan 63.4% untuk 10 MV. Penilaian padanan lengkungan menunjukkan bahawa padanan terbaik dicapai melalui model persamaan kemerosotan eksponensial tunggal. Kawasan di bawah lengkungan bara berkurang apabila masa antara penyinaran GeDOFs dan pembacaan TL meningkat.

K_{fad} ditentukan dengan membandingkan fungsi kemerosotan signal GeDOFs rujukan dengan yang diukur. Anggaran ketidakpastian yang berkaitan K_{fad} berada pada kadar 0.06% untuk CF dan 0.12% untuk FF. GeDOFs menunjukkan ciri kemerosotan signal yang dipengaruhi oleh selang masa bacaan TL dan tenaga sinaran. Apabila mengukur dos terserap daripada sinaran foton, adalah penting untuk mempertimbangkan faktor pembetulan kemerosotan signal untuk memastikan pengukuran dos yang tepat.

Kata kunci: Audit dosimetri; faktor pembetulan; gentian optik dop Ge; kemerosotan signal

Introduction

Advancements in dosimetry systems have led to the emergence of optical fibre thermoluminescence (TL) systems as effective relative dosimeters for measuring ionizing radiation doses. The evolution of optical fibre materials, particularly the utilization of Ge-doped SiO_2 optical fibres (GeDOFs), has transformed this amorphous glass into a viable alternative for TL-based dosimeters with comparable accuracy. Unlike LiF thermoluminescence dosimeters (TLD), GeDOFs benefit from high spatial resolution due to their micro size, water-impervious nature, and tailored sensitivity based on dopant concentration, which have consequently unlocked a variety of applications in the medical and industrial sectors (Begum et al. 2018; Benabdesselam et al. 2023; Kandan et al. 2021). In radiotherapy context, GeDOFs have found widespread adoption in measuring various beam energies, including gamma (Mat Nawi et al. 2015), photon (Lam et al. 2019; Noor et al. 2016), electron (Abdullah et al. 2022; Zakaria et al. 2020), and proton (Hassan et al. 2019). The exemplary dosimetric characteristics of GeDOFs position them as highly promising detectors for postal dosimetric audits in radiotherapy. A commercial version of GeDOFs has undergone testing for reference audit measurements in accordance with the guidelines of the International Atomic Energy Agency (IAEA) (Noor et al. 2017). Additionally, a more complex audit irradiation geometry has been conducted utilizing fabricated GeDOFs (Fadzil et al. 2022a), thereby, underscoring the viability of this remote dosimetry system.

Nevertheless, the performance of GeDOFs is profoundly impacted by the spontaneous TL intensity decay, attributable to the delayed readout time following irradiation. This inherent phenomenon, referred to as fading, entails the gradual dissipation of stored energy within the dosimeter material over time. Fading occurs notably when the dosimeters are subjected to heat (thermal annealing) or ambient light (optical bleaching), both of which can stimulate the TL intensity. In order to counteract the fading effect and ensure the accuracy of absorbed dose measurements, the introduction of a correction factor becomes essential (Pereira et al. 2016; Sorger, Stadtmann & Sprengel 2020). This fading correction factor can be determined either through calibration experiments or by employing mathematical models that characterize the fading behavior of the dosimeter. Importantly, it should be noted that not all dosimeters exhibit noticeable fading, and the necessity for a fading correction factor is contingent upon the specific type of dosimeter and the material employed.

The reduction in TL intensity over time following irradiation, which leads to the loss of dose information, poses a challenge to achieving high levels of accuracy in dosimetry assessments. This challenge is especially pertinent in postal dosimetry audits, where logistical arrangements and geographical distribution might result in delayed readouts of dosimeters. Consequently, to ensure precise dose evaluation, it becomes crucial to have comprehensive knowledge about the fading behavior of the TL detector and its attributes. Numerous efforts mentioned earlier have been made to investigate TL fading, aiming to integrate GeDOFs into dose measurements involving clinical beams. Despite the evident enthusiasm, these efforts have primarily yielded foundational descriptive insights and commentary, lacking a focused exploration of the complexities associated with fading kinetics and the formation of glow curve spectra. The present study, incorporating both measurable and computable analyses, is dedicated to examining the depletion of TL intensity, glow curve formation patterns, optimal curve fitting function, and the application of correction factors for GeDOFs.

Materials and Methods

Dosimeters Preparation and Experimental Configuration

In this study, GeDOFs utilized were locally fabricated through the modified chemical vapor deposition

(MCVD) method. These optical fibres were composed of standard silicon dioxide (SiO_2) but chemically enriched with germanium (Ge). Two variants of GeDOFs were manufactured: 1) a cylindrical fibre (CF) with a circular symmetric shape and a diameter of 483 µm, and 2) a flat fibre (FF) measuring 67.5 µm × 273 µm. The length of both fibers was standardized to 6.0 mm ± 0.5 mm. Additional details about the fabrication process were further explained elsewhere (Noor et al. 2016). Before irradiation, a dual-step thermal treatment was given to the GeDOFs, involving annealing at 400 °C for an hour followed by an eight-hour gradual cooling process in a furnace, aimed at resetting any potential accumulated background dose within the GeDOFs.

The GeDOFs were subsequently enclosed within an opaque polyethylene capsule, with ten samples of each variety being compiled to ensure precise mean values for the TL intensity, thereby minimizing potential errors. The Varian Clinac linear accelerator was employed to deliver nominal energies of 6 MV and 10 MV. To account for backscattered photons, the capsules were positioned atop a solid water phantom (Gammex, USA) measuring 30 cm × 30 cm × 10 cm. For the 6 MV irradiations, the capsules were sandwiched between 1.5 cm of bolus material, while for the 10 MV irradiations, 2.5 cm of bolus material was used. This arrangement was designed to expose the samples to the maximum dose corresponding to each type of beam energy utilized (Figure 1). The GeDOFs were subjected to simultaneous irradiation at the dose of 2 Gy, employing a dose rate of 600 MU/min, a source-to-surface distance (SSD) of 100 cm, and a symmetry field size of 10 cm × 10 cm.

TL EXTRACTION AND DATA ANALYSIS

The fading characteristics of the GeDOFs were assessed through TL measurements taken at intervals of 1, 2, 3, 10, 20, 30, 48, 71, and 106 days post-irradiation. To minimize exposure to extraneous ambient light and variations in temperature, the GeDOFs were placed within a light-tight container and stored at room temperature (~30 °C). TL intensity readings were conducted using a Harshaw 3500 TLD reader system (Thermo Fisher Scientific Inc, USA) following the recommended time-temperature profile (Fadzil et al. 2022b). This profile was chosen to achieve optimal glow curves while upholding the reliability and consistency of TL intensity measurements. Throughout the readout process, Windows®-based Radiation Evaluation and Management System (WinREMS) software was employed to measure TL intensity from the obtained experimental glow curves. The resulting data was then fitted into a one-phase exponential decay curve using GraphPad Prism. For the purpose of comparison, a best-fit natural logarithmic curve was generated using Microsoft Excel.

CORRECTION FACTOR AND UNCERTAINTY

In order to compensate for the fading effect when employing GeDOFs as dosimeters, a correction factor for fading is introduced. This fading correction factor

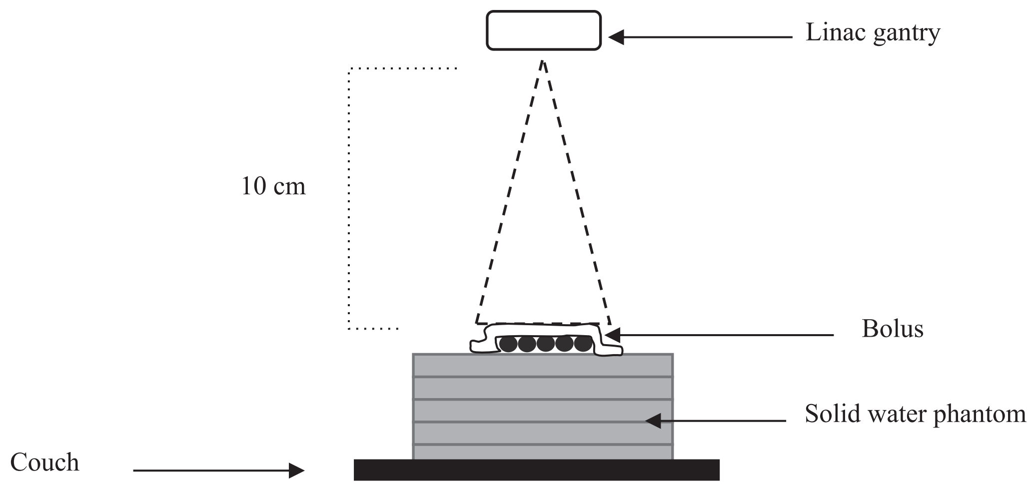


FIGURE 1. Schematic of GeDOFs MV irradiation setup

is established using mathematical models that delineate the fading characteristic of the GeDOFs. Through the application of the correction factor, the measured TL intensity can be appropriately adjusted to account for the fading effect, leading to a more precise assessment of the absorbed dose. The fading correction factor predominantly derives from the fading function (f_{fad}), where it is defined based on the one-phase exponential decay function in which this model provides a well-fitted decay graph. f_{fad} is the ratio of the TL intensity, f_t, of the GeDOFs, which was measured on day x, to the response, f_o, of the GeDOFs on the reference day x_o, as indicated in the following equation (Noor et al. 2014):

$$f_{fad} = \frac{f_t}{f_o} = \frac{f_o[(y_o - d)e^{-kx} + d]}{f_o} = (y_o - d)\ e^{-kx} + d \quad (1)$$

where y_o represents the y-value at x equals zero, d denotes the y-value at an infinite timespan, often referred to as a plateau, and k stands for the rate constant. These values – y_o, d and k – were derived from the exponential decay equation model.

Meanwhile, the fading correction factor, denoted as K_{fad}, is calculated as the ratio between the fading function of the reference dosimeter (RD) and the fading function of the field dosimeter (FD), expressed as:

$$K_{fad} = \frac{f_{fad}\,(x_{RD})}{f_{fad}\,(x_{FD})} = \frac{(y_o - d)e^{-kx_{RD}} + d}{(y_o - d)e^{-kx_{FD}} + d} \quad (2)$$

The assessment of uncertainty arising from TL intensity fading in GeDOFs was conducted using error propagation, as outlined by the subsequent equation:

$$u(K_{fad})^2 = \left(\frac{d(e^{-kx_{RD}} - e^{-kx_{FD}})}{[(y_o - d)e^{-kx_{FD}} + d]^2}\right)^2 u(y_o)^2 + \left(\frac{y_o(e^{-kx_{FD}} - e^{-kx_{RD}})}{[(y_o - d)e^{-kx_{FD}} + d]^2}\right)^2 u(d)^2 + \left(\frac{d(y_o - d)(e^{-kx_{FD}}\,x_{FD} - e^{-kx_{RD}}\,x_{RD}) + (y_o - d)^2\,e^{-(kx_{FD} + kx_{RD})}\,(x_{FD} - x_{RD})}{[(y_o - d)e^{-kx_{FD}} + d]^2}\right)^2 u(k)^2 \quad (3)$$

where x_{RD} refers to the time interval between irradiation and the readout of the reference dosimeter while x_{FD} signifies the time interval between irradiation and readout for the field dosimeter. $u(y_o)$, u(d) and $u(k)$ are the uncertainties associated with the coefficients y_o, d and k, which are derived from the non-linear regression analysis.

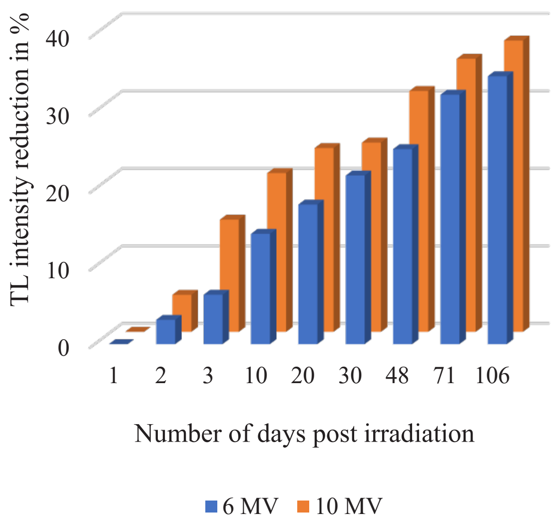
Results and Discussions

TL Intensity Reduction

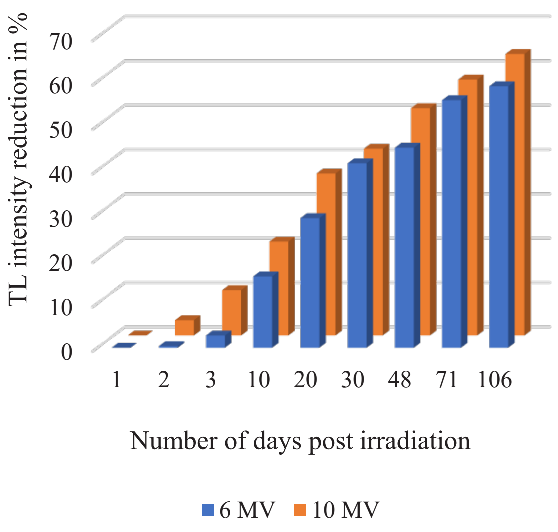
The fading outcomes were obtained through a comparison between the initial TL intensity recorded on the first day and the decaying signal observed on the 106th day following irradiation. Figure 2(a) and 2(b) depicts the variation in TL intensity fading of the GeDOFs as a function of post-irradiation days delay. Evidently, in the case of the 10 MV, there is a more pronounced reduction in TL intensity compared to the 6 MV. When scrutinizing the two types of GeDOFs, it becomes evident that the TL intensity decline was more significant in the FF variant, with losses of 58.9% and 63.4% for 6 MV and 10 MV, respectively, by the 106th day post-irradiation. In contrast, the CF experienced lower TL intensity loss, with reductions of 34.6% and 37.6% for 6 MV and 10 MV, respectively, by the same 106th day after irradiation. Throughout the time delay, CF exhibited an approximate maximum daily TL intensity loss of 0.36%, while the FF showed an average daily decay rate of up to 0.60%.

The decrease in TL intensity over time following the radiation exposure of GeDOFs takes place as a result of the spontaneous release of trapped electrons from shallow traps. The TL intensity originating from these shallow traps is governed by a lower energy barrier, which increases the likelihood of electrons escaping easily at relatively low temperatures (Bos 2017; Du, Feng & Poelman 2020). This scenario signifies that the TL intensity fades as time passes, irrespective of the consistent ambient temperature and lightless environment applied during the storage. Conversely, at higher temperatures, the thermal energy available to trapped electrons rises, enhancing the probability of their release and subsequent recombination thus resulting in the occurrence of rapid fading (Engin, Aydaş & Demirtaş 2010).

Fading can lead to an underestimation of the absorbed dose, resulting in inaccurate dose measurements. To maintain dosimeter accuracy over time and reduce the need for frequent recalibration or replacement, minimizing the fading rate is crucial. Various strategies can be employed to mitigate TL fading effects in dosimetry applications. Dosimeters should be stored in light-tight containers or covers to minimize light exposure (Fadzil



(a)



(b)

FIGURE 2. Percentage of TL intensity reduction of (a) CF and (b) FF following 6 MV and 10 MV photon irradiations

et al. 2022b) and kept at a controlled room temperature. Selecting dosimeter materials with minimal fading characteristics can also help alleviate fading effects. Additionally, applying correction factors based on the dosimeter's fading characteristics can compensate for fading effects in dose calculations (Noor et al. 2016).

BEST-FIT CURVE

All the collected data were normalized relative to the reading on the first day following irradiation. These illustrative curves serve as a consolidated representation of the numerous measured TL intensities for clarity. The lines connecting the points are provided as visual guides, with the fitness of each point indicated by the coefficient of determination (R^2). When making a visual estimation without specialized tools, there is not a noticeable differentiation between the decay fitting graphs produced by natural logarithmic (Figure 3) and one-phase exponential decay (Figure 4) functions. The data points seem to be evenly spread both above and below the curvature line. Additional evaluation was conducted utilizing a more objective approach, involving an examination of the fitness of each point through analysis of the R^2 value. For CF, both regression models exhibited a goodness of fit of 0.98. Conversely, for FF, the data showed better conformity with the exponential function, registering an R^2 of 0.99 as opposed to the logarithmic function's R^2 of 0.97. R^2 value close to 1 implies that the interval between irradiation and GeDOFs reading on subsequent days accounts for the variation in TL intensity production. The one-phase exponential model fits the data extremely well thereon.

Detailed assessment was done to each measurement point with a comparison between the measured (TL_{mea}) and calculated (TL_{cal}) TL intensity for all days post-irradiation as follows:

$$\Delta TL = \frac{TL_{mea} - TL_{cal}}{TL_{cal}} \times 100 \quad (4)$$

where TL_{mea} and TL_{cal} are the TL intensity measured by the TLD reader and calculated using the decay function, respectively. Of these two regression models comparison in Table 1, the exponential function has a lower percentage relative deviation between TL_{mea} and TL_{cal} for CF and FF, obtaining 1.82% and 1.99%, respectively, compared to 1.87% and 5.46% from the logarithmic function. This implies a stronger alignment of the measured data points when employing a one-phase exponential decay function, with the points closely clustered around the plotted line.

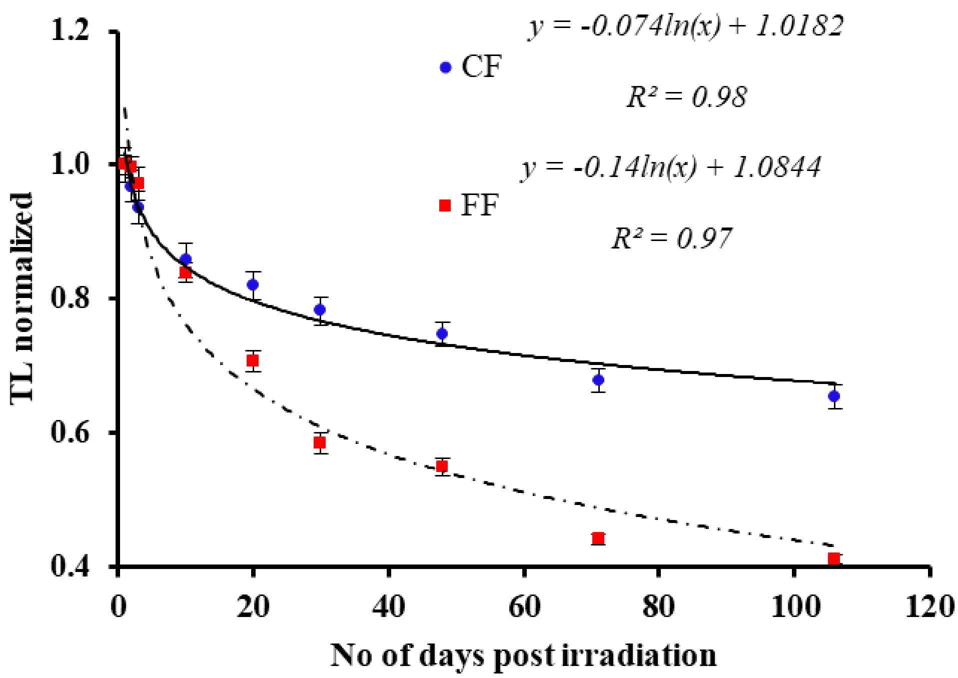


FIGURE 3. Natural logarithmic decay fit graph of TL intensity fading for GeDCOFs

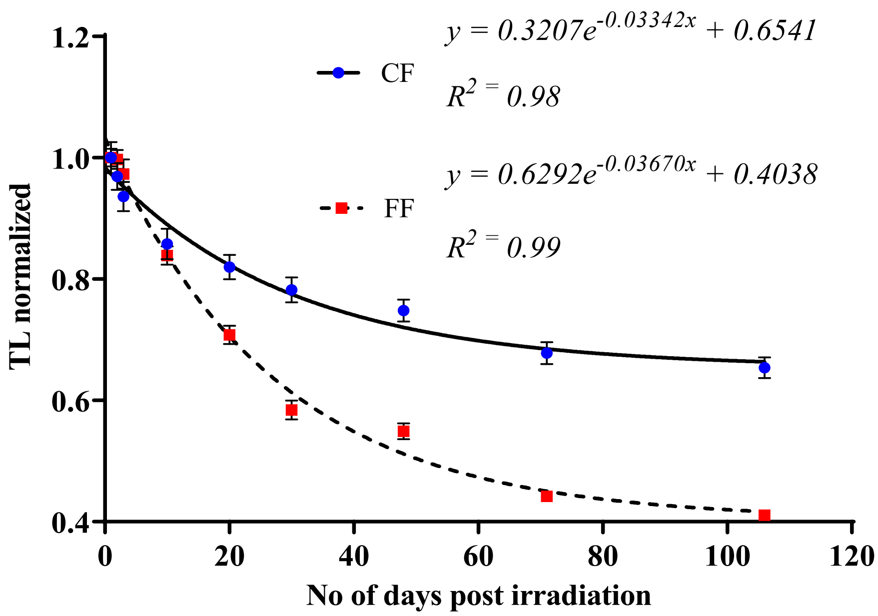


FIGURE 4. One-phase exponential decay fit graph of TL intensity fading for GeDOFs

Recent studies have explored the fading effect in TL using both exponential (Baghel et al. 2022; Sarasola-Martin, Correcher & García-Guinea 2021; Sen et al. 2021) and non-exponential decay functions (Gonzales-Lorenzo et al. 2022; Maruyama et al. 2020) for various luminescence materials. In typical fading behavior, the TL signal is expected to decay exponentially over time with a specific decay time constant, resulting in a concave line in the graphical representation of the decay over extended periods. Both exponential and logarithmic functions offer similar visual patterns based on the line connecting data points. However, when fitting individual single exponential decay functions to TL intensity for each dosimeter, the decay constants were observed to conform to a Gaussian distribution (Chen 2020). This suggests that fading functions can be characterized using a single group function with a decay constant equivalent to the mean of the individual decay constants found for each dosimeter reading. Consequently, the exponential model was deemed the most appropriate representation of the relationship between elapsed time and TL signal.

TABLE 1. Comparison of percentage relative deviation of calculated TL intensity based on the regression models used for GeDOFs. Negative deviations signify that the measured TL value is lower than the calculated TL value

CF					
Days post-irradiation	TL_{mea}	TL_{cal}		Δ Deviation (%)	
		Logarithmic	Exponential	Logarithmic	Exponential
1	1	1.02	0.97	-1.79	2.78
2	0.97	0.97	0.96	0.19	0.65
3	0.94	0.94	0.95	-0.07	-1.69
10	0.86	0.85	0.89	1.16	-3.65
20	0.82	0.80	0.82	2.92	-0.40
30	0.78	0.77	0.78	2.05	0.93
48	0.75	0.73	0.72	2.26	3.87
71	0.68	0.70	0.68	-3.53	-1.01
106	0.65	0.67	0.66	-2.83	-1.45
Average				1.87	1.82
FF					
Days post-irradiation	TL_{mea}	TL_{cal}		Δ Deviation (%)	
		Logarithmic	Exponential	Logarithmic	Exponential
1	1.00	1.08	1.01	-7.78	-1.02
2	1.00	0.99	0.99	0.93	0.82
3	0.97	0.93	0.97	4.51	0.53
10	0.84	0.76	0.84	10.16	-0.03
20	0.71	0.66	0.71	6.47	0.32
30	0.58	0.61	0.61	-3.91	-4.67
48	0.55	0.54	0.51	1.26	7.30
71	0.44	0.49	0.45	-9.33	-1.81
106	0.41	0.43	0.42	-4.80	-1.41
Average				5.46	1.99

GLOW CURVE FORMATION

Figures 5 and 6 illustrate the temperature-dependent TL intensity for CF and FF, respectively. GeDOFs exhibit broad peak glow curves, a characteristic commonly associated with amorphous silicon dioxide. In the case of CF, a single dominant peak is evident, positioned within the range of 259 – 269 °C. On the other hand, FF presents two distinct prominent peaks. The first, referred to as Peak 1, emerges at lower temperatures (233 – 251 °C), while the second, referred to as Peak 2, forms at higher temperatures (340 – 371 °C). When observing the glow curve spectrum of GeDOFs following a delay in post-irradiation reading, peak dwindling is observed, with no discernible alteration in shape. This is particularly noticeable in the low-temperature region (channel 1 – 100). A significant shift in the glow curve pattern of FF becomes apparent, with the area under the curve linked to Peak 1 progressively diminishing. As a result, the TL intensity associated with Peak 1 drops below that of Peak 2.

The TL glow curve from photon-irradiated GeDOFs displays a broad TL emission spanning various temperatures due to electron dispersion in multilevel energy traps within a silica medium. The assumption is made that the traps' levels, influenced by the defects engaged in the thermoluminescence process, are primarily governed by Ge impurities and structural anomalies introduced during fabrication (Termsuk, Sweeney & Shenton-Taylor 2022). The peak with the highest amplitude signifies the maximum liberated electrons at a specific temperature. As temperature rises, trapped electrons gain thermal energy, increasing their release likelihood, boosting TL intensity. Depth of traps is inferred from peak position, left shift indicating low-energy traps and vice versa. This complex GeDOFs curve usually manifests as a convolution of several peaks (Kandan et al. 2021), each one with distinct activation energy, emitting light in different temperature ranges. The glow curve area corresponds directly to the absorbed dose, ideal for dosimetry application.

In the comparison of two GeDOFs geometries' performance, the rate of fading in the FF is associated with the count of occupied shallow traps introduced during the vacuum-seal draw-down pulling phase of the fabrication process, a step that is absent in the manufacturing of CF. A new set of defect formations, referred to as strain defects, arises during the collapsing of FF's internal surfaces. This introduces another dimension of influence on TL intensity generation, as these defects create supplementary traps within the material (Bradley et al. 2015; Fadzil et al. 2018). Nevertheless, it appears that these additional traps increase the quantity of shallow traps, which in turn makes it easier for ambient temperatures to trigger the release of trapped electrons, resulting in a higher fading rate in FF. On the contrary, the central peak observed in the CF glow curve signifies a reduced number of shallow traps, where the prevalence of mid-energy level traps influences the formation of this single peak (Ghomeishi et al. 2015). This attribute enables CF to demonstrate superior performance, ensuring minimal depletion of stored radiation energy over time.

FADING CORRECTION FACTOR AND UNCERTAINTY

The fading correction values for GeDOFs were ascertained through the application of a one-phase exponential decay model, where TL intensity was plotted against the number of days. By employing Equation (3), the uncertainty associated with the fading value was calculated, considering a post-irradiation delay of 106 days. The estimated uncertainty for this correction factor stands at 0.06% for CF, doubling to 0.12% for FF. The notable disparity in uncertainty between the two types of GeDOFs can be attributed to how well the data fits the decay graph. This measure of uncertainty offers users a means to assess the reliability of the obtained data. The corresponding uncertainty values ($u(y_o)$, $u(d)$ and $u(k)$) for K_{fad} are detailed in Table 2.

Fading represents a substantial correction factor in the GeDOFs dosimetry system, as the latent signal within the dosimeter decays spontaneously over time, potentially leading to a false negative reading. One should remain vigilant about potential dose information loss, even to a partial extent, when employing GeDOFs for absorbed dose measurements, unless TL intensity acquisition occurs 24 h after irradiation. Consequently, there are other ways to eliminate the error due to fading other than the application of K_{fad}. One is the employment of a consistent fading time during dosimeter calibration. Maintaining a stable TL intensity production significantly reduces errors in radiation dose estimation. Any delay timeframe suitable for operations is permissible, but it should remain consistent across successive measurements. Another beneficial strategy involves utilizing unfading deconvoluted peaks obtained from the experimental glow curve to mitigate the fading effect (Theinert et al. 2018; Weinstein et al. 2003). However, since these deconvoluted peaks are characterized by multiple kinetic parameters, further in-depth investigation in this area is necessary to enhance comprehension.

TABLE 2. The value of uncertainty in the coefficient , *d* and *k* subjected to photon irradiations

Uncertainty of coefficient	CF	FF
$u(y_o)$	0.015	0.014
$u(d)$	0.025	0.021
$u(k)$	0.007	0.004

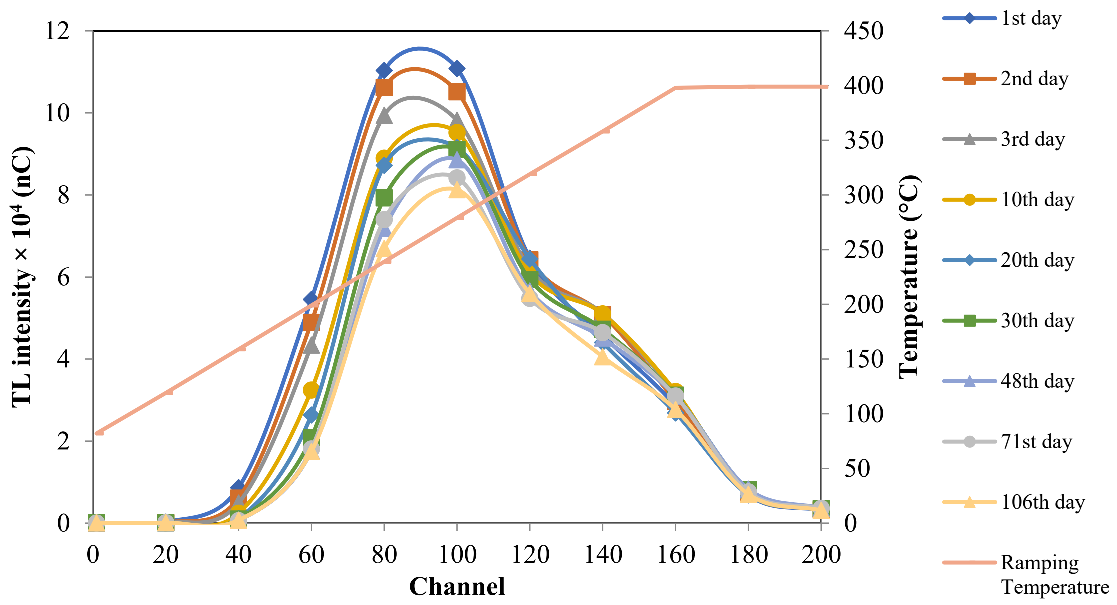


FIGURE 5. Depletion of glow curve formation of CF subjected to photon irradiation

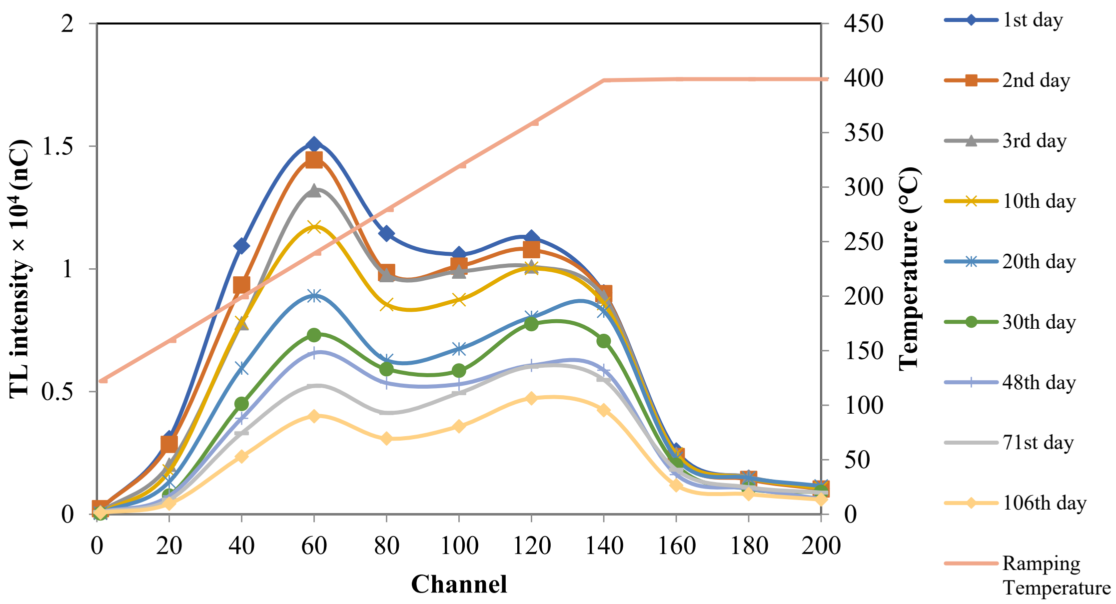


FIGURE 6. Depletion of glow curve formation of FF subjected to photon irradiation

Conclusion

Fading is of paramount importance when dealing with TL-based dosimeters designed for specific applications where long-term retention of the absorbed dose is vital. This research explores the fading behavior of GeDOFs microdosimeter, emphasizing TL decay characteristics and correction factors. GeDOFs exhibit the expected fading rate typical of amorphous systems. A lower fading rate ensures that the passive dosimeter's response remains consistent between calibration and measurement, reducing uncertainties in the absorbed dose calculations. This is crucial for quality assurance in radiotherapy and other applications where accurate dose measurements are critical.

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