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A systematic review on the silica fibre thermoluminescence dosimeters for medical applications

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Abstract

Silica fibre thermoluminescence (TL) dosimeters have demonstrated versatility in medical and industrial, offering high spatial resolution, sensitivity, water resistance, and insensitivity to electromagnetic fields. A systematic review focusing on the medical applications of silica fibre TLDs is conducted, highlighting the potential of these materials in medical radiation dosimetry. Despite some limitations, such as non-linearity at low energies and relatively high signal fading, silica fibre TL dosimeters have shown excellent TL performance. However, their application in clinical practice is yet to be established since the TL responses for a wide range of doses and energies are not accurately certified yet.

Keywords Silica glass fibre · Thermoluminescence dosimeter (TLD) · Glow curve · Dose–response · Signal fading

Introduction

Radiation dosimetry plays a crucial role in the diagnosis and treatment of a wide range of medical conditions, from cancer and cardiovascular diseases to neurological and metabolic disorders [1]. Accurate measurement and monitoring the radiation exposure are essential for ensuring the radiation safety of patients and healthcare professionals, as well as their well-being. However, radiation dosimetry in medicine is not without its challenges, particularly due to the fast-growing technologies in radiation medicine. Accurate measurement (with high spatial resolution), dose and radiation variations, tissue heterogeneity, patient size, and patient shape are the most challenging aspects of dosimetry, requiring highly accurate and reliable techniques to overcome. A schematic illustration of the typical amounts of skin dose at different medical applications of ionizing radiation is presented in Fig. 1. Due to the higher doses in radiotherapy, the applied dosimeters are required to be more stable, repeatable, and immune to environmental interferences such as humidity and temperature.

Due to their hands-on characteristics, thermoluminescence dosimeters (TLDs) are now broadly used in medical radiation for personal dosimetry, environmental monitoring, and dose distribution [2]. Thermoluminescence happens when an insulator or a semiconductor material emits light when heating after being exposed to ionizing radiation. During the exposure, the absorbed energy in TL material could excite the atomic electrons to higher energy levels, and when the material is subsequently heated with specific conditions, the exited electrons can return to their ground state while emitting visible light [3]. A broad range of TL materials are commercialized; for instance, TLD-100 (LiF:Mg, Ti) is a highly sensitive dosimeter that can measure a wide range of radiation doses, TLD-600 ($CaSO_4$:Dy) and TLD-500 (Al_2O_3:C) dosimeters which are efficient in the high-dose and high-energy environment (such as radiotherapy and nuclear power plants), and $Li_2B_4O_7$ dosimeters, which can be employed for radiation monitoring in medical and industrial sites. Despite their substantial advantages, conventional TLDs suffer from several restrictions. These include the costly production and readout procedures, as well as their relatively large sizes, which could limit their spatial resolution. In addition, the accuracy and sensitivity of conventional TLDs can generally be affected by environmental

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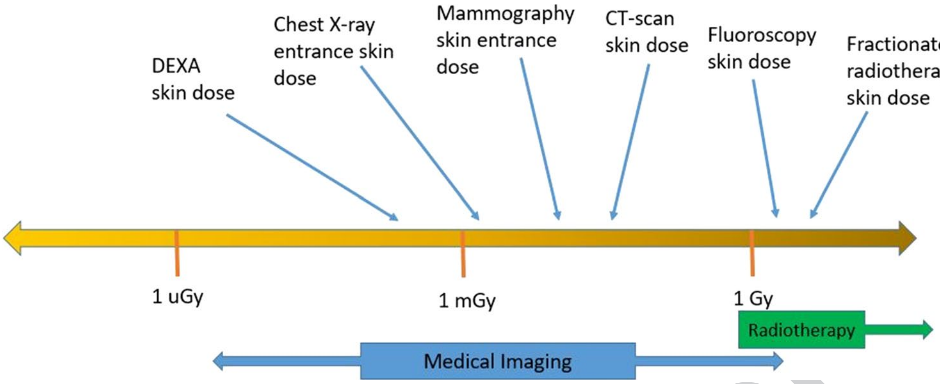

Fig. 1 Typical dose levels received in medical radiation

factors (such as moisture, temperature, and magnetic fields), so they hardly can be employed in intracavitary and image-guided modalities [4].

Numerous efforts have been conducted to find alternative materials for TL dosimetry. Patented by Amouzad and Rafiq [5], the silica optical fibres (basically developed for telecommunication purposes) have revealed potential in passive radiation dosimetry due to their TL sensitivity [6]. In comparison with the conventional commercially produced TLDs, silica-based optical fibres can provide a higher spatial resolution down to several tens of micrometres with a low production cost. These materials possess a non-hygroscopic nature and are not sensitive to electromagnetic interferences, thus showing high flexibility in radiation detection and promising capability for in vivo applications [7]. Throughout the last two decades, many researchers have performed detailed characterization of doped silica fibres and their applications in radiation detection [7–10]. Figure 2 presents the frequency of published articles over the last seven years. Silica fibre dosimeters have a wide range of applications, from radiation-based industries like environmental monitoring, food irradiation, and quality dose audits, to medical radiation disciplines such as radiotherapy, radiology, and nuclear medicine. The dependence of TL response on various factors is studied widely in the literature, including the impact of dosimeter size [11, 12], dopant material and concentration [13, 14], radiation type, dose and energy [15–18], radiation angle and source-to-detector distance [17, 19], and annealing procedure and dose history [20]. These factors have a significant influence on the TLD's accuracy, spatial resolution, dose/dose-rate dependency, linearity, reproducibility, signal fading, and energy response [11, 12, 21].

Given the widespread interest in the medical applications of doped silica fibre dosimeters, the authors were motivated to perform a study on the materials and methods, characterization results, and proposed applications mentioned in the literature with a statistical approach. While several review articles are already published in this field, to the best of our knowledge, a thorough systematic review containing a statistical analysis of the results and also potential applications of these TL dosimeters has not been reported. This paper summarizes the most recently published literature concerning

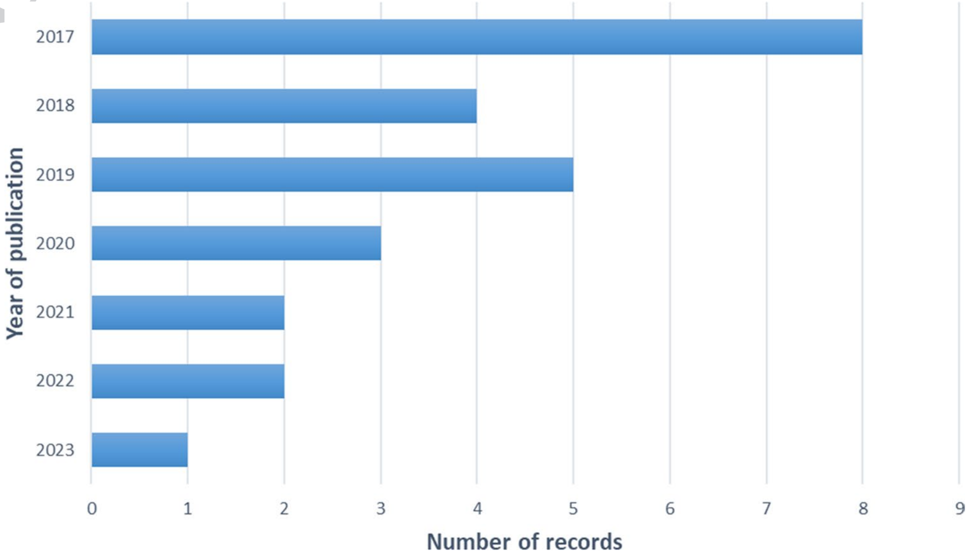

Fig. 2 Frequency of literature over the assessed time period

the structure of silica fibres and their characterization. We discuss the behaviour of different silica-based dosimeters while interacting with various radiation types, and also their potential applications in medicine. Furthermore, the research gaps and challenges, saturated topics, as well as proposed solutions in the literature are emphasized.

Methodology

This systematic review is performed by conducting a broad literature search on the studies that investigated glass fibre TLDs and their applications in medical science, specifically medical imaging, and radiotherapy. The search strategies and the number of results for each database are summarized in Table 1. Since our focus was on TL dosimeters, the studies on radioluminescence (RL), photoluminescence (PL), optically stimulated luminescence (OSL), and Cherenkov radiation features of silica-based dosimeters are excluded. In addition, the studies on non-medical applications, non-fibre dosimeters (including bead, powder, and gel dosimeters), and also plastic fibres are not included in this review. Since we intended to review the most recent articles that studied medical applications of this specific type of dosimeters, a seven-year time period is imposed and all the publications from 2017 are collected. The original articles from scholarly journals are assessed, and the conference proceedings/posters, editorials, and review articles are excluded. The literature search was performed on February 17th, 2023 using Scopus, ScienceDirect, and Sunway University library (Tun Hussein Onn Sunway Library) websites.

Results and discussion

A total of 1451 records were retrieved by the literature search, and 4 additional records were added through citation searching. After the duplicate removal, and screening of the title, abstract, and full-texts, 25 original articles were included in this systematic review. The flow diagram of the literature selection process is depicted in Fig. 3.

Table 2 summarizes all the reviewed publications along with their key characteristics and major findings. A glance at this table reveals that the majority of reviewed articles are concentrated on the therapeutic aspects of silica fibre dosimetry, while the functionality of these dosimeters in diagnostic radiation applications has also been confirmed to be comparable with conventional TLD materials.

Fibre structure

Initially intended for telecommunication, silica fibres have also drawn attention for their thermoluminescent responses to ionizing radiation, as mentioned before. This feature has led to many studies exploring various types of these fibres for dosimetric applications. Silica fibres are generally manufactured through the Modified Chemical Vapor Deposition (MCVD) process, which is the preferred method for high-performance optical fibres [38]. This involves the preparation of a preform (made of SiO_2), deposition of a soot layer (a fine powder made of a mixture of gases such as germanium tetrachloride, $GeCl_4$, and silicon tetrachloride, $SiCl_4$), heating to a high temperature to consolidate the soot and finally core and cladding deposition by a similar procedure [39]. Despite the satisfactory TL response of un-doped fibres, the introduction of a dopant material to the fibre's core creates extrinsic defects that increase the generation of electron–hole pairs after exposure to ionizing radiation, and in turn, the sensitivity of the dosimeter. The fibre's cladding can also be made of either pure silica or a doped material [40]. The frequency of different structures used in the reviewed articles are summarized in Table 3, as well as the radiation sources and clinical applications of silica fibres. In this context, the term 'structure' involves the geometrical form of the fibre, the dopant material used, and the dopant concentration.

Table 1 Summary of the search strategy

Database	Search Query	Period of study	Document Type	Source Type	Language	Number of records
Scopus	(Silica OR glass) AND (fibre OR fibre) AND dosimet* AND (medic* OR radiotherapy)	2017–2023	Article	Journal	English	132
ScienceDirect	(Silica OR glass) AND (fibre OR fibre) AND (dosimeter OR dosimetry) AND (medical OR medicine OR radiotherapy)	2017–2023	Research Articles	Journal	English	402
Sunway University Library	(Silica OR glass) AND (fibre OR fibre) AND (dosimet*) AND (medic* OR radiotherapy)	2017–2023	Article	Academic Journal	English	917

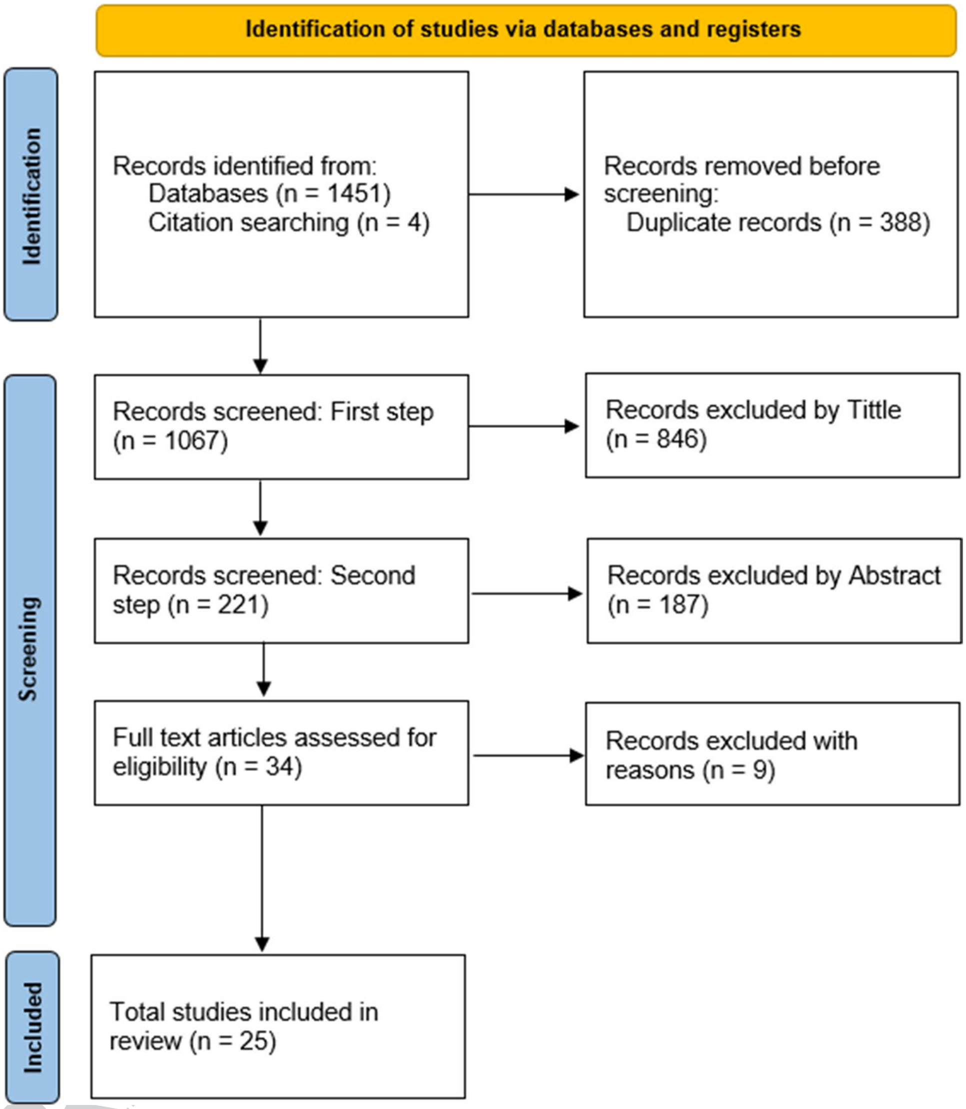

Fig. 3 Flow diagram of the literature selection process

Fibre forms

The dosimetric performance of silica fibres can be significantly influenced by their geometrical form [41]. The initial studies by Mahdiraji et al. [42] and Girard et al. [43] focused on the irradiation responses of commercially available cylindrical Ge-doped single-mode telecommunication fibres (SMF) and multi-mode telecommunication fibres (MMF) for TL dosimetry. Encouraged by promising results, these fibres received extensive interest, with various research groups aiming to characterize and evaluate their potential in medical dosimetry. Subsequently, fabricated cylindrical fibres (CF) and capillary optical fibres (COF) were examined for their medical applications, both were made using the aforementioned MCVD process. Afterwards, the flat fibres (FF) were developed as a collapsed version of COF through low vacuum pressure application during the drawing procedure [44]. The collapsing lead to the fusion of capillary walls and the creation of more defects, potentially enhancing the TL yield. Another innovative micro-structured fibre, known as photonic crystal fibre (PCF), was also explored and identified as a more efficient TL dosimeter compared to ordinary CF [45]. The PCF can be produced of silica or polymer using a "stack-and-draw" method [46], which includes the fusion of the outer surfaces of a bundle of capillary fibres together. A random or regular distribution of longitudinal holes can be observed in the cross-section of the PCFs. Further improvement in the TL performance of these fibres was achieved by collapsing the PCF holes through the fibre drawing procedure, which is referred to as collapsed PCF or PCFc. Figure 4 shows the cross-sectional SEM images of 4 different silica fibre forms.

Many researchers have compared these various forms in terms of their TL performance. In an early study, Bradley et al. [45] drew a comparison between the TL response of three un-doped fibres (COP, FF, and PCF) and two forms

Table 2 A summary of the materials and methods and main findings of the reviewed literature (PCF = Photonic Crystal Fibre, PCFc = Collapsed Photonic Crystal Fibre, FF = Flat Fibre, CF = Cylindrical Fibre, SMF = Single Mode Telecommunication Fibre)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
1	Begum et al. (2023) [22]	PCFc	Ge	Photon (6, 10 MV)	Photon radiotherapy	The TL response was independent of beam energy The threshold doses were 28 and 27 mGy for 6 and 10 MV photon beams, respectively Reproducibility within 3% for 4 Gy irradiations PDD agreed within 5% between PCF and ionization chamber
2	Fadzil et al. (2022) [23]	CF, FF	Ge	Photon (6, 10 MV)	Photon radiotherapy	All fibres exhibit a linear dose–response from 1 to 3 Gy with $R^2 > 0.99$ Minimal energy dependence, with reproducibility within a 3% deviation The fading rates at day 106 after irradiation were 37.6%, 63.4%, and 14.2% for CF, FF, and TLD-100 respectively, The mean ratios of on-axis dose, wedge transmission, and output factor for silica fibres to TLD-100 were 1.014, 0.991, and 1.013, respectively
3	Abdullah et al. (2022) [18]	CF, FF	Ge	Electron (6, 9, 12, 16, 20 MeV)	Electron radiotherapy	At 120 days, 26% and 20% fading for CF and FF respectively Linear dose response for 6 MeV electrons with $R^2 = 0.985$ The electron therapy audit findings are within the acceptable range of 5% tolerance, with the highest deviation of 4% for FF
4	Alyahyawi et al. (2021) [24]	FF	GeB	Gamma (^{60}Co- $E_{mean} = 1.25$ MeV)	Radiosurgery	Performance of GeB-FF and TLD-100 was studied by measuring scattered radiation from cranial cavity radiosurgery Both types could measure < 1% to < 0.1% of prescribed dose Uncorrected GeB-FF results indicated absorbed doses in the pelvis, chest, and neck approximately 1.4, 1.2, and 1.5 times higher than TLD-100

Table 2 (continued)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
5	Abdul Sani et al. (2021) [25]	FF, PCF	GeB	Electron (2, 9 MeV)	Electron radiotherapy/Sterilization dosimetry	The dosimeters showed linear response for doses from 4 to 50 Gy, with sub-linear behaviour beyond this dose The deconvolution showed five glow peaks, the three first peaks were attributed to oxygen atoms in the silica network and the last two peaks are related to boron atom The borosilicate glass slide showed promise for electron dosimetry in radiotherapy and sterilization modalities
6	Zakaria et al. (2020) [26]	CF, FF	Ge	Electron (6, 9, 12 MeV)	Electron radiotherapy	Strong linearity ($R^2 > 0.99$) and minimal dependence on dose rate for all fibres The 2.3 mol% FF outperformed other fibres, with the highest sensitivity and minimal TL fading for a period of 3 months The FF exhibited a relative difference of less than 2% in PDD curves
7	Rais et al. (2020) [27]	CF, FF	Ge	Photon (RQT 8: 100 kV, RQT 9: 120 kV, RQT: 10: 150 kV)	CT scan	Deconvolution of the glow curves revealed five distinct glow peaks for all fibres (P1 to P5) P1 was the dominant peak in most cases, except for the 6 mol% Ge-FF fibre, where P3 was the dominant peak
8	Nawi et al. (2020) [28]	CF, FF	Ge	Electron (6, 9, 12, 16, 20 MeV)	Electron radiotherapy	Highly linear dose–response within the range of 1 to 4 Gy The highest response was from smallest 6 mol% Ge-doped FF, exceeding the TLD-100 by a factor of 1.1 Lowest signal loss (around 26.9% within 120 days) for smallest 6 mol% Ge-doped FF Excellent reproducibility, with a CV of less than 2% and 4% for 6 and 8 mol% fibres, respectively No energy and dose rate dependency for all the examined TLDs

Table 2 (continued)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
9	Lam et al. (2019) [17]	FF, CF	Ge	Photon (6, 10 MV)	Small-field photon radiotherapy	The reproducibility for FF and commercial fibre dosimeters was between 2 and –6% while being less than 14% for CF High linearity up to 80 Gy with $R^2 > 99\%$ The angular independence is less than 3% High signal fading of 25% for the FF at 31 days after irradiation
10	Moradi et al. (2019) [19]	CF	Ge	Photon (50 kVp, 6 MV)	Intraoperative radiotherapy	The correction factors and combined uncertainty of 9.5 to 12.4% were established for the application of silica fibre TLDs in Intraoperative radiotherapy (IORT) The minimum detectable dose was about 50 mGy For the same dose, the TL response for 5 cm applicator was 31% lower than 1.5 cm applicator
11	Rais et al. (2019) [29]	CF, FF	Ge	Photon (RQT 9: 120 kV)	CT scan	Supralinear behaviours for doses below 2 mGy in both the fabricated and commercial fibres For doses above 4 mGy, all dosimeters show f(D) close to 1, indicating a linear response The Ge-doped FF had the highest TL sensitivity, being 84 and 87 times that of TLD-100 for 2.3 and 6 mol%, respectively
12	Hassan et al. (2019) [15]	CF	Ge	Proton (150 MeV), Gamma (^{60}Co- $E_{mean} = 1.25$ MeV), Photon (6, 10 MV), Electron (6 MeV)	Proton therapy/Radiotherapy	High TL response for 1 to 10 Gy dose, with linearity index close to 1 ($R^2 > 0.99$) The minimum detectable dose (MDD) of 10.7 mGy The signal fading was lesser than 19% at 96 days post-irradiation

Table 2 (continued)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
13	Alyahyawi et al. (2019) [30]	CF	Ge	Photon (80, 100, 140 kVp 6, 10 MV)	CT scan/ radiosurgery	Dose to the eye lens did not exceed 0.5 Gy at any of the 20 radiotherapy centres when using SRS-related technology Mean dose to the lens is around 0.03 to 0.08 Gy for CT scan modalities The Ge-doped silica fibres and glass beads showed potential for dosimetry of central and peripheral eye lens
14	Bradley et al. (2018) [31]	CF, FF, PCF, PCFc	Ge, B, Br	Photon, Alpha (5 to 7.5 MeV)	Radionuclide therapy	The TL response of collapsed PCFs was higher than uncollapsed ones Signal fading of Ge-PCF, Ge–B-PCFc, and TLD-100 was 21%, 15%, and 7%, respectively The SiO_2 doped fibres are less hygroscopic than TLD-100, showing potential for use in alpha particle radiotherapy dosimetry
15	Begum et al. (2018) [32]	FF	Ge	Photon (6, 10 MV)	Photon radiotherapy	The glow curve peaked at 249 °C and was not affected by repeating the measurements The TL responses were dose rate dependent for 100 to 500 MU/min The effective atomic number (Z_{eff}) was 13.37, which was close to the Z_{eff} for human bone (11.6–13.8)
16	Moradi et al. (2018) [13]	CF	P, Er, Ge, Al, Tm, borosilicate	Gamma (^{60}Co- $E_{mean} = 1.25$ MeV), Electron (2 MeV)	Ultra-high dose radiotherapy	Saturation levels were from 5 kGy for Ge-doped to 80 kGy for Al-doped fibre The borosilicate fibre showed acceptable linearity, saturation in 100 kGy, and fading of 5–6% after 24 h, which have made them suitable for single-use The fibres with lower concentrations saturated at higher doses

Table 2 (continued)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
17	Alyahyawi et al. (2018) [33]	FF, disc PCF	Ge, GeB	Photon (60 kVp 25, 28, 32, 35 kVp)	Dental X-ray/Mammography	For mammography, the Ge–B-FF and Ge-disc showed 7 and 3 times higher sensitivity than TLD-100 For fibres, the lowest responses happened at 25 kVp, and the highest response happened at 32 kVp For TLD-100 the highest response happened at 28 kVp For dental radiography, the Ge–B-FF showed 3 and 3.9 times higher sensitivity than Ge-disc and TLD-100
18	Alawiah et al. (2017) [16]	FF	Ge	Electron (2.5 MeV)	Ultra-high dose electron radiotherapy	A critical dose limit (CDL) for FF was 5 times higher than that of TLD-100 After 1 MGy radiation dose, TLD-100 and FF needed to be annealed at more than 400 °C temperature
19	Moradi et al. (2017) [34]	SMF	Ge	Photon (30 kVp, 6 MV)	Photon radiotherapy/Diagnostic X-ray	The angular dependency for 30 kVp X-ray was up to 35% in the air For 6 MeV beam, the values were 20%, 10%, and 3% in air, on the surface, and in-depth, respectively
20	Lam et al. (2017) [35]	CF, FF	Ge	Photon (6 MV)	Photon radiotherapy	A linear TL response for commercial and cylindrical fibres The structure of glow curves was unchanged for different preheat temperatures The highest peak intensity (PI) was for CFs
21	Moradi et al. (2017) [20]	SMF	Ge	Gamma ($E_{mean} = 1.25$ MeV)	Gamma radiation therapy	The effect of dose history on the TL response of SMF dosimeters was indicated A 100 Gy dose history can increase the response 1.72 times The impact of dose history is due to the lower re-trapping rate after saturation The TL response for higher sensitivity SMF stabilized after a dose history of 100 Gy, whereas the response became steady after a dose history of 20 Gy for the fibre with lower sensitivity

Table 2 (continued)

No	Author	Fibre form	Dopant	Radiation type and energy	Clinical applications	Major findings
22	Mahdiraji et al. (2017) [12]	CF	Ge	Photon (6 MV)	Photon radiotherapy	The fibre core is responsible for the highest TL signal Cladding thickness had minimum impact on the TL signal Higher sensitivity for smaller sizes after normalization to the mass or cross-sectional area The shearing effect could be contributed to this finding
23	Alyahyawi et al. (2017) [36]	SMF, PCFc	Ge, GeB	Photon (80, 100, 120 kVp)	Low-dose radiography	PCFc-Ge–B, PCFc-Ge, and SMF showed 15, 10, and 2 times higher sensitivity than TLD-100 30 days after irradiation, the signal fading was 20%, 13%, 8% for three fibres, and 7% for TLD-100
24	Begum et al. (2017) [14]	CF	Ge	Photon (6, 10 MV)	Photon radiotherapy	Highest TL response for 4 mol% Ge-doped fibres and least response for 25 mol%, which was due to the quenching effects All fibres had linear dose–response The primary dosimetry peak happened at about 244 °C for the most sensitive fibre (4 mol% concentration)
25	Hassan et al. (2017) [37]	FF	Ge	Proton (150, 210 MeV), Gamma (1.25 MeV), Photon (6 MV), Electron (9 MeV)	Proton therapy/Radiotherapy	Dose linearity with $R^2 = 0.99$ for Ge-doped FF at the dose range from 1 Gy up to 10 Gy Reproducibility with the SD between 0.86% and 6.41% Signal fading after 96 days was 24% and 18% for Ge-doped FF and TLD-100, respectively The examined fibres showed promise in proton dosimetry

Table 3 Frequency of different fibre properties and radiation sources in the literature

Item	Frequency in literature (%)
Fibre form	
Cylindrical Fibre	63
Flat Fibre	54
Capillary Optical Fibre	43
Photonic Crystal Fibre	21
Dopant material	
Ge	88
Ge–B	21
Other	8
Dopant concentration	
2.3 mol%	21
4 mol%	8
6 mol%	38
8 mol%	8
Other/not specified	46
Radiation source	
Photon	75
Electron	33
Gamma (^{60}Co)	21
Proton	8
Clinical application	
Therapeutic	88
Diagnostic	25

of Ge-doped fibres (COP, FF) under 0.5–8 Gy dose from 6 and 20 MV photons. The results of this study showed a significantly higher response from FF other than COP. This could highlight the impact of generating new defects through the fusion of the capillary fibre's inner surface. The study also showed an even greater response from PCF, which was also claimed to be attributed to the effect of surface fusion. The dose responses for these three fibre forms extracted from this study are presented in Fig. 5. The authors also examined the impact of Ge-dopant for capillary and flat fibres exposed to 6 MeV electron irradiation, revealing that the addition of the dopant could enhance the TL response by almost 10 times. However, the results were still lower than that of TLD-100 as the gold standard.

Another investigation was conducted by Mahdiraji et al. [41] on several types of silica fibres exposed to 6 MeV electrons. They compared the F300 ultra-pure fused silica fibres, relatively pure fused (PS), Ge-doped, and GeB-doped fibres in terms of the TL response and glow curves. The results obtained from the TL responses across a range of doses, from 0.5 to 8 Gy, further confirmed the superior performance of flat fibres compared to capillary fibres. Moreover, the inclusion of dopants was found to enhance efficiency, as the GeB-doped fibres exhibited higher TL responses compared to the Ge-doped fibres. The glow curves acquired by these researchers also showed a second peak for FFs compared to COFs, likely due to the contribution of additional defects in the structure of collapsed FF dosimeters (Fig. 6).

Bradley et al. [39] discussed the production techniques of silica-based media and their challenges, as well as their potential for TL dosimetry. The first attempts for characterization of collapsed PCF with Ge and GeB dopants are also discussed, presenting and comparing the dose responses with TLD-100 and TLD-200. Using 80 kVp X-ray irradiation, the authors stated that PCFs could offer a higher TL response than that of TLD-100, however, TLD-200 could outperform these fibres.

Table 4 summarizes the benefits and drawbacks of the four main silica fibre forms, making a clear comparison based on the literature. It is important to note that according to the characteristics of different forms of silica fibres, the choice of dosimeter will depend on the specific applications and dosimetry conditions. Thus said, a careful balance between the TL sensitivity, spatial resolution, stability, and cost must be considered.

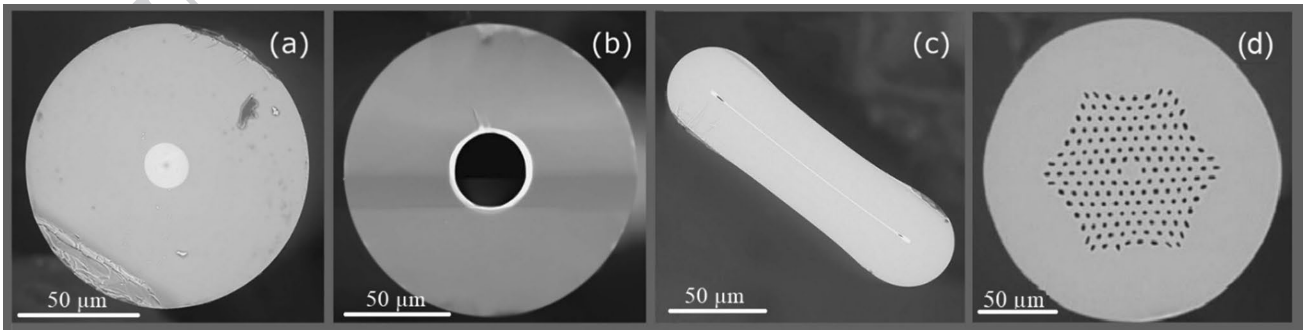

Fig. 4 Different silica fibre forms: **a** cylindrical fibre (CF), **b** capillary optical fibre (COF), **c** flat fibre (FF) (Ghomeishi et al. [47]), and **d** photonic crystal fibre (PCF) (Bradley et al. [45])

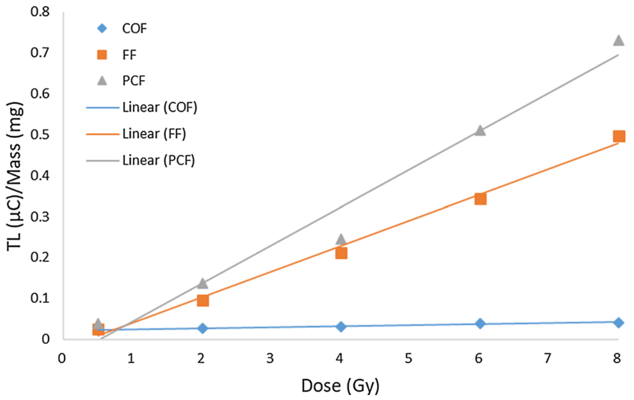

Fig. 5 The TL response for three fibre forms (COF, FF, and PCF). Reproduced from Bradley et al. [45] with permission

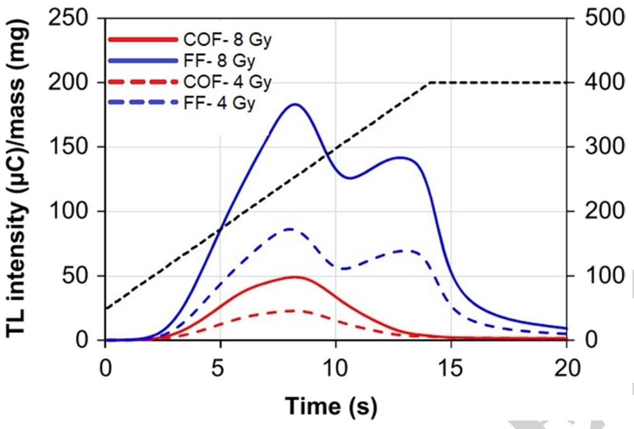

Fig. 6 The glow curves for COF and FF dosimeters. Reprinted from Mahdiraji et al. [41] with permission

Dopant material and concentration

The response of silica fibre TLDs to ionizing radiation strictly depends on the material and concentration of the dopants, as well as the type of radiation. One of the main roles of the dopant material is to increase the sensitivity of the TL dosimeter to radiation by increasing the number of electron traps and the ability to detect lower doses. Moreover, the dopants can enhance the stability of dosimeters by reducing the signal fading, which is the loss of the TL signal over time. The dopant can also improve other dosimetric properties as well, such as linearity and energy response [48]. In practice, a limited number of elements are proposed as dopant material for silica fibres TL dosimeters. So far, germanium (Ge), boron (B), thulium (Tm), phosphorus (P), aluminium (Al), and silver (Ag) are investigated in the literature and have shown promise [13, 39, 49]. As shown in Table 3, Ge-doped silica fibres are the most frequent types. The cost-effective manufacturing process of Ge-doped optical fibres has proven germanium as the most commercially favourable element for both telecommunication and dosimetry purposes. Comparing the Ge-doped and Ge–B-doped silica fibres in terms of their TL yield, several studies have also stated the superiority of the Ge–B dopant [36, 41, 49, 50]. However, while the presence of boron would also add the extra capability of neutron detection to the silica fibre, the costly fabrication procedure of boron-doped fibres remains a major challenge [49].

The concentration of dopant in silica fibre could also affect the TL performance depending on the radiation properties. In general, a certain level of dopant concentration can improve the TL sensitivity, while exceeding this amount will

Table 4 Advantages and disadvantages of different forms of silica fibres

Fibre form	Advantages	Disadvantages
Capillary Optical Fibre (COF)	Potential for high-dose radiation measurements due to high saturation dose (100 Gy) [13]	Limited sensitivity compared to CF and FF [41] Difficult to handle and read because of the delicate geometry
Cylindrical Fibre (CF)	High peak intensity (PI) of glow peaks [35] Relatively low signal fading, with 8% after 30 days [36]	Sensitivity is about 5 times lower than PCF [36] Angular dependence up to 35% in the air [34] Limited spatial resolution due to the cylindrical geometry
Flat Fibre (FF)	Up to 31 times higher sensitivity than COF, depending on the dopant material [41] Higher sensitivity than CF [26] Better stability over time and lower signal fading than CF (20% versus 26% after 120 days) [18] Higher spatial resolution due to the obtainable smaller sizes More convenient to handle and read than CF	Asymmetric geometry Additional stage in its production procedure [44]
Photonic Crystal Fibre (PCF)	Superior TL performance compared to other fibre forms [31]	Higher signal fading than CF [36] Limited availability due to the complex fabrication procedure and higher costs compared to other forms

result in quenching effects, where the dopant absorbs some of the emitted light and reduces the TL signal. Therefore, it is important to carefully optimize the dopant concentration based on the experimental condition to achieve the desired level of sensitivity. Different techniques could be applied to evaluate the dopant concentration in silica fibre, including refractive index profiling (RIP), scanning electron microscope energy-dispersive x-ray analysis (SEM–EDX), and proton-induced x-ray emission or proton-induced gamma emission (PIXE/PIGE) [39].

The effect of dopant concentration is studied by Noor et al. [51], where 6, 8, and 10 mol% Ge-doped silica fibres were compared in terms of their TL characteristics under 6 and 10 MV photon irradiation. Among these three, the 6 mol% concentration showed the highest TL signal with the least amount of signal fading. This result was then confirmed by Begum et al. [14], which examined the dosimetric properties of 4, 5, 7, and 25 mol% concentrations of Ge-doped silica fibres subjected to 6 and 10 MV photons. Their results also indicated a TL yield of 37% of the standard TLD-100 for 4 mol% concentration as opposed to a mere 2% for 20 mol%. Figure 7 shows the acquired glow curves presented by this study, clearly indicating the impact of dopant concentration. Using different dopant materials, Moradi et al. [13] have also compared three concentrations of phosphorus (1.3, 3.6, and 7.8 mol%) in a P-doped silica fibre and two concentrations of aluminium (2, 4, and 5.1 mol%) in Al-doped silica fibre. According to their study, the silica fibres with higher concentrations of dopant were saturated earlier (at lower doses), indicating the greater potential of low concentrations for high-dose detection. However, as Table 3 demonstrates, a large proportion (38%) of the reviewed literature have conducted their studies using a 6 mol% concentration of dopant material, highlighting the need for future studies on an optimal dopant concentration.

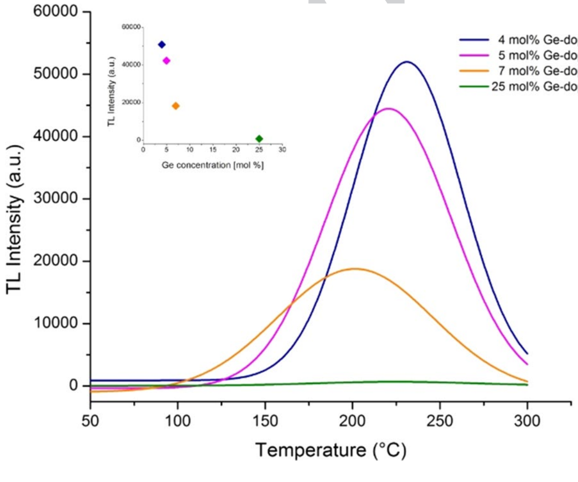

Fig. 7 The glow curves and TL intensity for typical tailor-made Ge-doped silica fibres with four different dopant concentrations. Reprinted from Begum et al. [14] with permission

Fibre size

The size of silica fibre plays an important role in determining its TL properties. The effect of fibre diameter and core-to-cladding ratio is extensively studied by Mahdiraji et al. [12], where the TL performance of Ge-doped cylindrical silica fibres is measured for different fibre diameters and core-to-cladding ratios. The authors assessed the glow curve, linearity, and sensitivity of 6 and 8 mol% fibres with five different diameters. To modify the core-to-cladding ratio, the samples were etched using HF (hydrofluoric) acid solution to reduce the diameter of their cladding. After normalizing the TL yield to the fibre core mass or cross-sectional area, the authors concluded that smaller core diameters result in more sensitive dosimeters due to a higher concentration of defects in the core. However, this can also lead to a non-linear response at high doses due to the saturation of defects. Conversely, larger core-to-cladding ratios result in a more linear response at high doses but may reduce sensitivity as defects are dispersed over a larger area. Additionally, the larger cladding layer can provide more mechanical stability to the fibre, making it more durable and resistant to damage. It is concluded that the optimal size and core-to-cladding ratio in glass fibre dosimetry depends on the specific application and the desired sensitivity and linearity of the dosimeter. The impact of fiber size on the structure of the glow curve is depicted in Fig. 8 from Mahdiraji et al. [12], comparing five different Ge-doped CFs.

Radiation sources

The irradiation response of TLDs is directly dependent on the type and energy of the radiation, as well as the specification of the dosimeter itself. The selection of a suitable

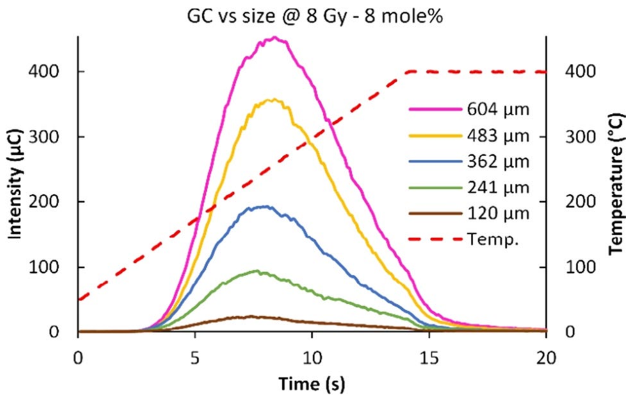

Fig. 8 The glow curves for various silica fibre sizes with 8 mol% Ge-dopant. Reprinted from Mahdiraji et al. [12] with permission

dosimeter for each particular medical application plays a crucial role in dose assessment. In radiotherapy, for instance, the durability and constancy of the performance of a dosimeter in high-dose rates are of great importance, as well as the stability in harsh environmental conditions such as humidity, temperature, and pressure variation [52]. In brachytherapy, providing high dynamic range and high spatial resolution are crucial aspects of the dosimeter owing to the existence of very high dose gradients [53]. In the case of low-energy X-rays, on the other hand, adequate sensitivity to low-dose radiation (in the range of mGy) would be in demand, since these energy ranges are now used in both radiation therapy and medical diagnostics. As demonstrated in Table 3, a significant percentage of the literature had focused on photon radiation, while proton and neutron dosimetry have not been extensively studied. This is likely due to limited access to hadronic irradiation facilities. In addition, the majority of studies are dedicated to the performance of silica fibres in high-energy therapeutic radiation. The extracted data could show a clear need for further research on proton, neutron, electron, and low-energy X-ray therapies.

X-ray and gamma-ray

According to our literature assessment, the performance of silica-based fibre dosimeters upon irradiation with photons is broadly investigated. As for low-energy diagnostic X-rays radiation, Alyahyawi et al. [33] investigated the GeB-doped FF and Ge-doped discs for dosimetry of dental radiography and mammography. The TL sensitivity, linearity, energy response, and fading of the glass fibres in low radiation levels were examined in this work. The delivered dose from dental radiographic irradiation was from 5 µGy to 1.3 mGy, and for mammography was from 0.4 to 28 mGy. Despite the reported high sensitivity, especially for Ge–B FF, sub-linearity behaviour for doses less than 1 mGy is noticeable for this dosimeter. The signal fading is also reported as 22% for Ge–B FF and 14% for Ge-doped discs over a period of 15 days after irradiation, which is respectively three and two times higher than that of the TLD-100. The TL response for the examined dosimeters in this work demonstrated the high performance of silica fibres and their superiority over TLD-100 for medical low-dose detection.

The TL performance of silica fibres in the diagnostic radiation energy range was also investigated by Alyahyawi et al. [36]. They used an X-ray tube to deliver 0.1- to 10 mGy doses into PCFc-Ge, PCFc-Ge–B, SMF, and TLD-100 dosimeters. According to their results, a relatively high energy dependence for the PCFc was reported, with the lowest response contributed to 120 kVp x-rays. However, the measured sensitivities for PCFc-Ge–B, PCFc-Ge, and SMF dosimeters were substantially high, approximately 15, 10, and 2 times greater than that of TLD-100. Due to the acceptable TL performance and also the low fading (0.4–0.5% per day), these fibres are claimed to be capable candidates for medical diagnostic dosimetry.

As we noted earlier, most of the studies on silica fibres rely on high-energy therapeutic photons, which are typically generated using clinical linear accelerators (LINAC). Noor et al. [54] applied Ge-doped silica fibres for postal radiotherapy dose audits. High-energy photon beams with 6, 10, and 15 MV energy were used to deliver a range of doses from 5 cGy to 10 Gy to the fibre dosimeters, which proved a linear response over the whole energy range. The TL response of the fibres was independent of dose rate, angular, and temperature. However, the response was energy-dependent for photon energies from 6 to 15 MV. In another work, Begum et al. also examined the dose rate dependency [32] for Ge-doped FF after photon exposure. The dose rates used in this work were 100, 200, 300, 400, and 500 MU/min, and a fixed amount of the dose was delivered by adjusting the irradiation time. In this context, a monitor unit (MU) is equivalent to 1 cGy dose. The TL response acquired in their study remained rather constant by changing the dose rate, which approved the dose rate dependency of these silica fibres. The authors also highlighted the necessity of more comprehensive work in lower dose rates for accurate dosimetry. However, the overall acceptable performance of silica-based fibres could demonstrate their capability for therapeutic dosimetry at routinely applied dose rates and energies in radiotherapy modalities [49].

The widespread applications of ^{60}Co gamma rays in radiotherapy have also drawn attention to utilizing silica fibres for dose evaluation in this field. Due to the emission of relatively high-energy photons during the decay of the ^{60}Co isotope into ^{60}Ni (1.17 MeV and 1.33 MeV, $E_{mean} = 1.25$ MeV), this radioisotope is an ideal radiation source for the treatment of various types of cancer by sparing of the skin (e.g. for head and neck, lung, brain, and prostate cancers) [55]. The characterization of 6 mol% Ge-doped FF under ^{60}Co gamma-ray irradiation was performed by Nawi et al. [56], comparing the key features of this TL dosimeter against TLD-100. The glow curves for four different dimensions of flat fibres were acquired, as well as the dose–response, sensitivity, fading, and reproducibility. The glow curves have a simple peak within the range of 320–370 °C, presenting a simple trap distribution. Moreover, considering the linearity with a correlation coefficient larger than 0.94 for all the sizes, and reproducibility with a coefficient of variation (CV) lower than 4%, it is claimed that the Ge-doped FF could be suitable dosimeters for gamma-ray detection. It is further stated that the fibres with the smallest size have shown the highest TL yield, which is consistent with the previously mentioned studies.

Electron

Due to the limited range of electrons in soft tissue, electron radiotherapy can offer several advantages over photons, including targeted radiation delivery, lower radiation exposure to healthy tissue, and shorter treatment duration. Several studies have conducted experiments on the utilization of silica fibre dosimeters for electron radiotherapy dosimetry. Nawi et al. [28] used tailor-made silica fibres with 6 and 8 mol% Ge-doped to compare different forms and sizes in terms of TL yield in electron dosimetry. All the fibres had acceptable linearity in the 1–4 Gy dose range, and the reproducibility test showed a standard deviation of less than 2% for 6 mol% and less than 4% for 8 mol% cylindrical and flat fibres. Overall, they concluded that the smallest size FF (85 μm × 270 μm) with 6 mol% concentration shows the highest TL response, as well as the lowest signal fading (around 26.9% at 120 days after irradiation). These results are partially consistent with the study of Zakaria et al. [26], where CF and FF optical fibres with 2.3 and 6 mol% Ge-doped were studied under the influence of electron beams. Electrons with 6, 9, and 12 MeV energy were used to deliver a 1 to 5 Gy dose to the medium, acquiring excellent linearity and TL yield. They also showed that the smaller size 6 mol% FF (620 μm × 165 μm) has better dose dependency than other forms, and the larger 2.3 mol% FF (643 μm × 356 μm) has higher performance in signal fading.

Moreover, Zakaria et al. suggested the rather stable behaviour of 6 mol% FF in dose rate response could reveal its potential in FLASH radiotherapy, which is a class of radiation therapy that delivers an ultra-high dose of radiation in a very short period of time, with the dose rates of 40 Gy/s or higher. However, accurate correction factors for higher dose rates are needed to be established in future research. The behaviour of Ge-doped FF under ultra-high electron doses (1 Gy to 1 MGy) is also investigated by Alawiah et al. [16]. The TL sensitivity of FF dosimeters was shown to be lost with the increase in dose, though it is 4.8 times higher than TLD-100 in the studied dose range. The authors suggested that this sensitivity reduction could be related to the interaction of external electron radiation with inner shell atomic electrons.

Proton

Proton therapy is a precise form of radiation treatment that can target cancer cells while sparing healthy tissues. This can result in a lower risk of radiation damage to tissues, fewer side effects, and higher treatment success. The complexity of radiation-tissue interactions and the beam scattering in this method has raised the demand for highly accurate dosimetry and treatment planning system. The potential applications of silica fibre TLDs in proton therapy have been of interest mainly due to providing high spatial resolution and TL sensitivity [57–59]. Hassan et al. [15, 37] performed extensive research on 2.3 and 6 mol% Ge-doped FF and CF dosimeters subjected to proton, gamma, photon, and electron irradiations. Using 150 and 210 MeV protons, a wide range of doses (up to 10 Gy) was delivered to the dosimeter, and the TL characteristics were investigated. Their experiments on CF dosimeters showed a higher TL response for higher concentrations. In contrast, the 2.3 mol% Ge-doped FF had a greater dose response, better reproducibility, and the least signal loss than the other examined fibres. Nevertheless, similar to other radiations, the sublinear response of the silica fibres at lower radiation doses is again observed for proton dosimetry.

Neutron

Neutron dosimetry faces many challenges because of the complex nature of neutrons as uncharged particles, such as the diversity and energy dependence of neutron interactions. Additionally, the lack of proper cross-section data and the difficulty of providing adequate shielding are other obstacles to accurate neutron dosimetry. Few studies have evaluated the TL performance of silica fibres in response to neutron irradiation. In an early study, Hashim et al. [21] studied commercial Al- and Ge-doped silica fibres exposed to fast neutrons from a ^{241}Am–Be neutron source with 10.6 GBq activity, and for periods of 1, 2, 3, 5, and 7 days. The experiment showed a sensitive linear response for Ge-doped fibre, while the Al-doped fibre did not show a notable TL response. Verified by the Monte Carlo simulations using MCNP5 code, the TL response is shown to be increasing for longer irradiation times, as it is displayed in Fig. 9.

Characterization of silica fibres

A broad range of output parameters are reported in the literature concerning the characterization of fibres and their TL performance. These include the glow curve, dose response, sensitivity, reproducibility, and signal fading. In this section, a more detailed discussion of the characterization of silica fibres and the related output parameters is provided.

Glow curve

The glow curve is a graphical representation of the TL response of a material, showing the emitted light as a function of temperature after exposure to ionizing radiation. The glow curve is of great importance in TL dosimetry as it can provide information about the energy and dose of the radiation received, allowing accurate and precise determination of radiation exposure for various applications. The impacts of different parameters such as fibre form, fibre size, and

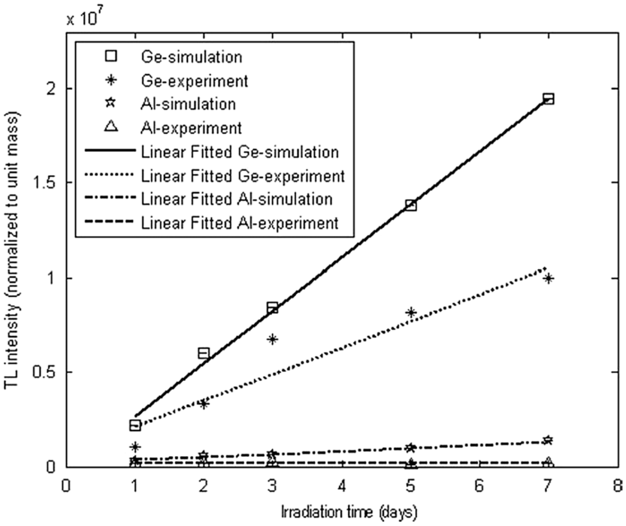

Fig. 9 The TL response of Ge-doped and Al-doped fibres irradiated by fast neutrons. Reprinted from Hashim et al. [21] with permission

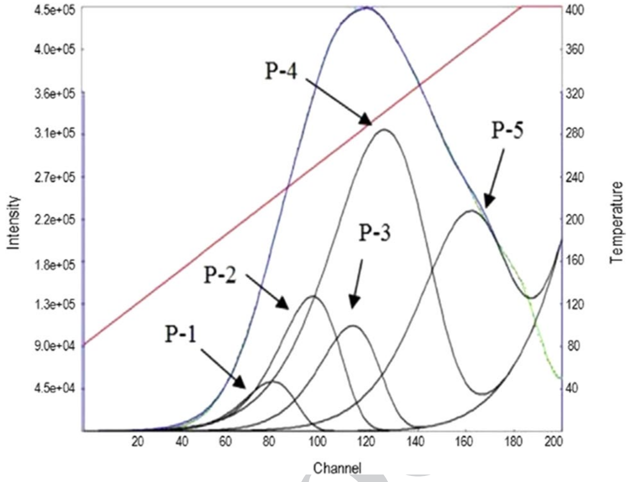

Fig. 10 The de-convoluted glow curves for a 6 mol% Ge-doped CF irradiated by a 6 MV photon beam with 600 MU/min dose rate. Reprinted from Lam et al. [35] with permission

the dopant concentration on the intensity and shape of the glow curve are elaborated in previous sections. The intensity of the glow curve is recognized to be affected by the radiation type, energy, and also the readout heating rate due to the changes in trapping parameters [2]. The kinetic parameters of glow curves are investigated by Lam et al. [35] for 6 mol% Ge-doped flat and cylindrical silica fibres under 6 MV photons. In their study, the WinGCF software was used to acquire the deconvolution of glow peaks and the kinetic parameters such as maximum temperature (T_{max}), activation energy (E_a), and peak integral (PI). The deconvoluted glow curves included 5 glow peaks, with the first peak attributed to the electrons from the lowest temperature trap, and the fifth peak from the highest temperature trap (Fig. 10). Their results showed that the peak integral (PI) for CF dosimeters were higher than that of the FF and commercial fibres. The peak integral (PI) is a measure of the total amount of light emitted from a TLD during the thermal stimulation measurement, calculated by integrating the area under the glow peak of the TL glow curve. The authors also evidenced the consistency of T_{max} for different heating rates for the same radiation exposure type.

Rais et al. [27] also studied the structure of glow curves for 2.3 mol% and 6 mol% Ge-doped CF and FF, under different doses of kilo-voltage X-ray irradiations typically used in CT scan modalities. The kinetic parameters are also investigated using the glow curve deconvolution analysis. According to their results, the shape of glow curves was highly dependent on the fibre structure, as can be observed in Fig. 11a. Additionally, their deconvolution analysis also revealed 5 curves (P1–P5), consistent with the previously mentioned study of Lam et al. [35]. The deconvolution of the double-peaked glow curve is shown in Fig. 11b, demonstrating the dominance of P3 which provided the greatest PI among all the examined beam types. The authors consequently concluded that the high peak temperatures and acceptable dose dependency could prove these silica fibres as suitable candidates for CT dosimetry. However, more extensive research on the characteristics of glow peaks from various types of silica fibres and radiation sources is recommended [31].

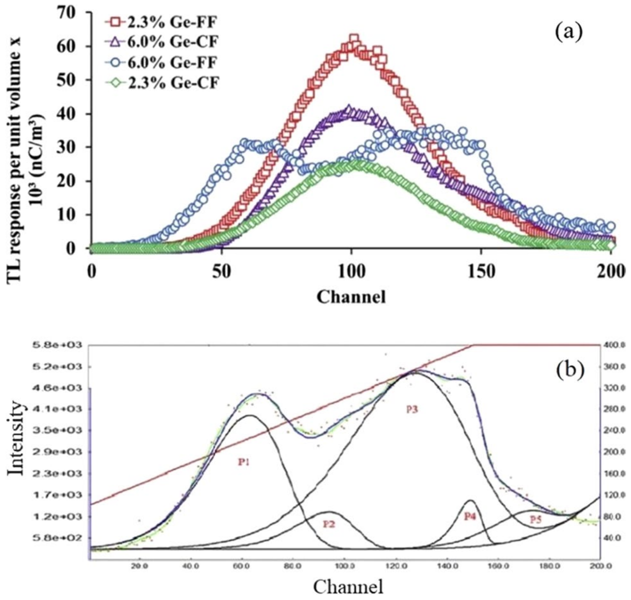

Fig. 11 The TL glow curves for four different silica fibres (**a**), and the deconvoluted glow curves for 6 mol% Ge-FF (**b**). Reprinted from Rais et al. [27] with permission

Dose response

The dose response of a TL dosimeter refers to the relationship between the absorbed dose of radiation and the corresponding TL signal emitted by the dosimeter. This response is crucial in medical dosimetry as it allows for accurate measurement and assessment of radiation doses delivered to patients during medical procedures, ensuring the safety and effectiveness of radiation therapy treatments. The linearity index, f(D), is a measure of the linearity of the dose response of a radiation detector, defined as the ratio of the detector response at a high dose to the response at a low dose. An f(D) value of 1 indicates the perfect linearity, however, the dose response of TL dosimeters is typically non-linear (f(D) > 1) [15]. This nonlinearity must be taken into account when calibrating TL dosimeters for use in medical dosimetry.

The f(D) is calculated by Rais et al. [29] for 2.3 and 6 mol% Ge-doped FF and CF dosimeters exposed by diagnostic 120 kVp X-ray, delivering doses from 2 to 40 mGy. The results are compared against commercial fibres and TLD-100, as it is shown in Fig. 12. Based on their outcomes, the fabricated and commercial fibres showed supralinear behaviours at doses less than 2 mGy, however, the f(D) was inclined to 1, and for all these dosimeters for the above 4 mGy and up to 40 mGy.

work of Alyahyawi et al. [33], where Ge–B-doped FF and Ge-doped discs are utilized for radiation dosimetry in low-energy photons of dental radiography and mammography systems. According to their results, the Ge–B-doped FF showed greater TL response over the Ge-doped discs and TLD-100, revealing its capability to linearly measure the diagnostic doses down to 2 mGy with a coefficient correlation higher than 98%.

In the therapeutic domain, the dose response linearity of Ge-doped FF with various sizes was calculated by Abdul Rahim et al. [60] for 6 MV photons at 400 cGy/min and with a dose range of 1–10 Gy. They showed that all the flat fibre sizes expressed linear responses in this dose range with correlation coefficients higher than 99.4%. Based on their results, both TL responses and correlation coefficients were higher for flat fibres with smaller sizes. However, a different behaviour was observed for these flat fibres under ultra-high radiation doses according to Alawiah et al. [16] study. As a part of their comprehensive work, the authors of this study calculated the linearity index for Ge-doped FF and compared it to TLD-100. A 2.5 MeV electron beam is used to deliver a range of doses (from 1 Gy to MGy) to the fibres. A supralinear behaviour was observed for Ge-doped FF with a rapid increase in f(D), from around 5 at 1 kGy to about 9 at 10 kGy. Future research may need to establish appropriate correction factors due to the non-linear response of silica fibres at very low and ultra-high doses. This highlights the importance of further investigating the behaviour of silica fibres within this dose range.

Sensitivity

The TL sensitivity refers to the ability of a thermoluminescent material to detect and accurately measure the absorbed radiation doses. It is defined as the ratio of the change in the TL signal to the change in the absorbed dose and is influenced by factors such as the type of material, dopant concentration, and the method of preparation. The TL sensitivity can typically be presented as the TL yield per unit dose, normalized by the unit mass of the TLD. As a commonly used parameter in TL dosimetry, many have included sensitivity in their reports, presenting a credible tool for making comparisons between various types of silica fibres.

Zakaria et al. [26] examined the TL response of different structures of fabricated Ge-doped silica fibres and commercial fibres receiving megavoltage electron irradiation. Along

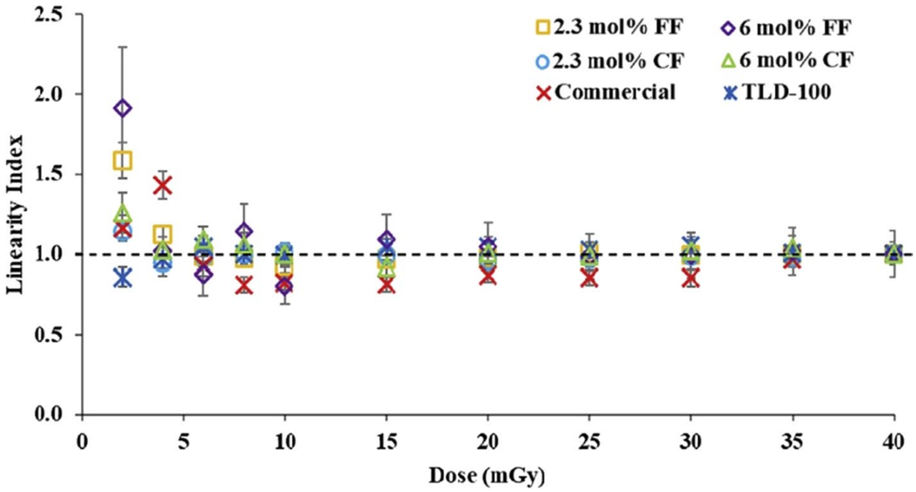

Fig. 12 The linearity index vs delivered dose. Reprinted from Rais et al. [29] with permission

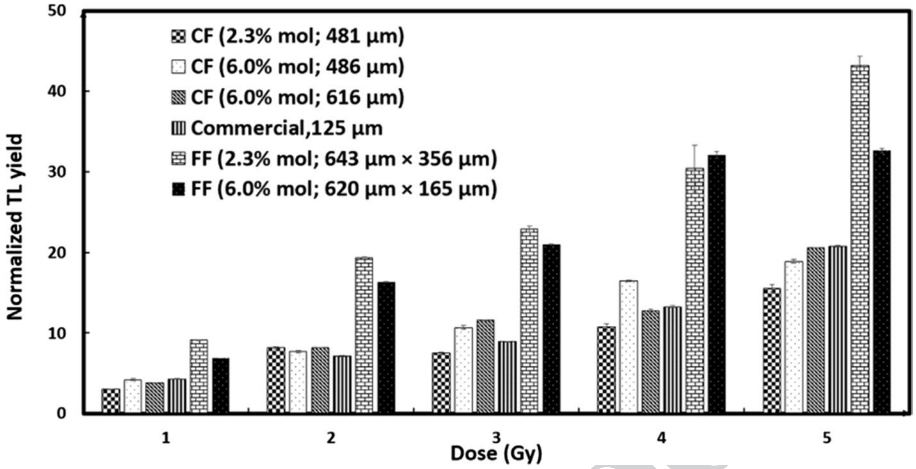

Fig. 13 A comparison of TL sensitivity of various silica fibre structures. Reprinted from Zakaria et al. [26] with permission

with the other main characteristics, the TL sensitivity is also measured for all the samples. Figure 13 shows the sensitivity of silica fibres for 6 MeV electrons across the doses range of 1–5 Gy extracted from Zakaria et al. [26]. The figure illustrated an overall rising trend in TL yield for all the fibres by increasing the radiation dose. It is also observable that the TL yield for flat fibres with different sizes and dopant concentrations was significantly higher than that of other types. For application in diagnostic X-ray imaging, the previously mentioned study by Alyahyawi et al. [36] have also reported the TL sensitivity for PCFc-Ge, PCFc-Ge–B, SMF, and TLD-100. Utilizing an X-ray tube with 80 kVp potential, their measurements showed that the PCFc-Ge–B dosimeters had the highest performance with the TL sensitivity of 39 times more than TLD-100.

Reproducibility

The sensitivity of a TL material might experience variations after being repeatedly used. The reproducibility factor refers to the ability of these devices to consistently produce similar results when exposed to the same radiation dose under identical conditions. It is a critical characteristic that ensures the reliability and accuracy of TL dosimetry measurements. To assess reproducibility, repeated measurements are performed using multiple dosimeters, and statistical analysis techniques such as standard deviation are employed. The acceptable TL reproducibility for medical applications is a CV of less than 5% [2]. According to the literature, silica fibre TLDs have generally shown excellent reproducibility through different investigations [48, 49, 61].

Entezam et al. [62] used 6 and 10 mol% tailor-made Ge-doped silica fibres to measure the dose from electron, megavoltage photon, and ^{60}Co gamma irradiations. The characterization of silica fibres resulted in a linear dose response, with reproducibility from 1 to 5%. However, the TL response of these fibres was rather dependent on energy, radiation field size, and irradiation angle. The cylindrical Ge-doped fibres with 2.3 and 6.0 mol%, and commercial CF with 4.0 mol% concentration are used by Hassan et al. [15] to examine their behavior for proton radiation dosimetry. A considerable dose–response was observed in this work for Ge-CFs which surpassed the dose response for TLD-100. As for the linearity index, f(D), the maximum deviation from 1 for 2.3 mol% Ge-CF was 9% at 1 Gy, and for 6.0 mol% Ge-CF was 4% at 7 Gy. Nevertheless, the reproducibility test showed a maximum CV of 9%, which was higher than the medically acceptable threshold. The authors then stated that this value could be decreased by performing a screening process on the fibres before using them in the final experiment.

In a recent study, Begum et al. [63] used collapsed PCF to obtain the percentage depth doses (PDD) for 6 and 10 MV photons. The PDD from their experiments were validated by the standard ionization chamber with a maximum of 5% disagreement. They also established a threshold dose for PCFs as 28 mGy for 6 MV and 27 mGy for 10 MV. These are the minimum amount of doses that can induce a TL response distinguishable from the background. The reproducibility of these fibres after five cycles of irradiation and readout using a 4 Gy dose was reported to have a CV of less than 2.5%. According to our literature assessment, most studies have reported CV values between 2 and 4% for the reproducibility of different types of silica fibres. This is lower than the maximum acceptable level in medical dosimetry (5%), which confirms the appropriate performance of silica fibre dosimeters in terms of reproducibility.

Signal fading

Signal fading refers to the phenomenon where the TL signal of a dosimeter decreases with time after irradiation. Several reasons can be contributing, including thermal fading, optical fading, and radiation-induced fading. The radiation quality, fibre structure, and storage conditions of the dosimeters can play a role in determining signal fading. In general, the less fading a dosimeter has over time, the more accurate and reliable the readout results will be. The TL signal of silica fibre dosimeters typically experiences a faster loss during the first 7–10 after irradiation, while it remains more stable afterwards [51].

The signal fading for Ge-doped FF dosimeters subjected to 150 MeV protons was calculated by Hassan et al. [37]. From their experiments, 96 days after the irradiation, the signal loss of 18%, 24%, and 58% for TLD-100 chips, 2.3 mol%, and 6.0 mol% fibres, respectively (Fig. 14). These percentages were the normalized values to day three post-irradiation, suggesting that silica fibres performed less effectively than TLD-100. The fading percentages for Ge–B FF, Ge-doped disc, and TLD-100 subjected to low-energy X-ray irradiation were reported by Alyahyawi et al. [33] to be 22%, 14%, and 7%, respectively. A comparison between different sizes of cylindrical and flat Ge-doped silica fibres was conducted by Nawi et al. [28] in terms of their TL performance. According to their results related to signal fading, the signal loss was less than 50% for 6 mol% Ge–doped fibres at 120 days after irradiation. For both the fibre forms, the smallest ones had the least signal fading with around 29.7% for cylindrical and 26.9% for flat fibre. Comparing CF and FF under a 2 Gy dose from a 9 MeV electron beam, Abdullah et al. [18] reported a loss of 26% and 20% for CF and FF, respectively. The TL yields in their calculation were measured 120 days post-irradiation and were normalized to the 15th day after irradiation. This study also reaffirmed the lower signal loss for smaller fibre sizes.

A relatively better performance was observed by using PCF dosimeters according to the previously discussed study by Alyahyawi et al. [36]. They reported signal fading of 20%, 13%, and 7% for PCFc-Ge and PCFc-Ge–B over 30 days after 80 kVp X-ray irradiation. These results were consistent with the former study conducted by Rozaila et al. [50], where the signal loss was measured over 35 days after 80 kVp X-ray irradiation delivering 1 Gy dose. They reported a fading of 21% for PCFc-Ge, and 15% for PCFc-Ge–B, while the loss was 7% for TLD-100.

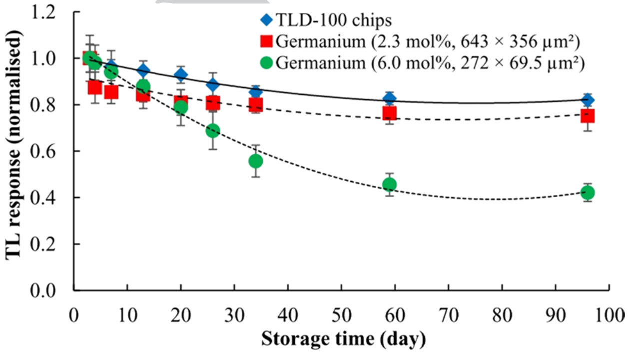

Fig. 14 A comparison between the signal fading of Ge-doped FF and TLD-100 chips. Reprinted from Hassan et al. [37]

Overall, despite the satisfactory results for some fibre types (such as PCF and small-size FF), the signal fading for silica fibre TLDs reported in the literature is still not comparable with the well-established TLD-100. Therefore, more improvements seem to be needed in this regard, such as exploring other dopant materials or evaluating the effect of post-irradiation annealing.

Other fibre characteristics

Effective atomic number (Z_{eff}) Z_{eff} represents the tissue equivalence of the TL dosimeter, which is essential for accurate measurement of absorbed dose in different tissues and organs of the human body. Different tissues in the human body have varying Z_{eff} values, with soft tissue having a value of 7.42 and bones ranging from 11.6 to 13.8 [64]. Therefore, the dosimeter material should have a Z_{eff} value close to that of the irradiated tissue to ensure accurate dose measurement. While the dopant material primarily determines the Z_{eff} [65], the values for silica fibres in the literature are generally within the range of 12–15 [49, 50]. This could closely approximate the Z_{eff} of human bone, making these silica fibres suitable candidates for medical dosimetry applications. However, further research is necessary to establish accurate correction factors for estimating the dose delivered to soft tissue.

Minimum detectable dose (Threshold dose) Minimum detectable dose (MDD) refers to the lowest dose of radiation that can be reliably detected and measured by a TL dosimeter. It represents the minimum amount of radiation required to produce a measurable TL signal above the background noise level. It is calculated from the following formula [66]:

$$\mathrm{MDD} = (\mathrm{BG}_{\mathrm{mean}} + \mathrm{PMT}_{\mathrm{mean}} + 2\sigma)/\alpha \tag{1}$$

where $\mathrm{BG}_{\mathrm{mean}}$ is the mean TL background signal and $\mathrm{PMT}_{\mathrm{mean}}$ is the photo-multiplier noise signal, both obtained from five unirradiated but annealed fibres, σ is the standard deviation of background signals, and α is the slope of the TL response. In the early study of Mahdiraji et al. [42], the MDD is calculated using the above-mentioned equation for SMF-1 with 4.9 wt% and SMF-2 with 4.3 wt% Ge concentrations, as well as the TLD-100. Three electron beams with 6, 9, and 20 MeV energies were used to irradiate the samples, and the average MDD values for SMF-1, SMF-2, and TLD-100 were about 6, 39, and 19 mGy, respectively. Their results indicated the impact of dopant concentration on MDD, where higher concentrations could detect lower doses.

Using low-energy beta irradiation from ^{90}Sr, Bajuri et al. [67] calculated the MDD for Ge-doped cylindrical fibres and stated that these fibres can detect low-energy electrons down to 0.026 and 0.029 mGy for 604 µm and 483 µm diameter CFs. The behaviour of these fibres when subjected to an Am–Be neutron source (4.5 MeV) and a proton beam (150 MeV) is also investigated in this work. The MDD for neutron detection using the 604 µm CF was determined to be 0.55 mGy, while for the 483 µm CF, it was found to be 0.38 mGy. The same values for proton radiation were 19.16 mGy for 604 µm and 31.81 mGy for 483 µm diameter. Their findings showed the ability of silica fibres to linearly ($R^2 = 0.97$) measure the low-dose radiations, with lower MDD for beta and neutron radiation using the larger CF. This superiority of larger CF in terms of MDD was also affirmed by Noor et al. [51] for high-energy photon irradiations. Two sizes of cylindrical fibres with 6, 8, and 10 mol% concentrations of Ge were examined in their work. In addition to observing lower MDDs for larger sizes, it was found that a lower concentration of dopant could lead to the least MDD. Specifically, the minimum doses of 27 mGy and 126 mGy were detected using 604 µm and 241 µm diameter fibres, respectively.

Angular (directional) dependency The angular dependency of a TL dosimeter is an important characteristic to consider when using dosimeters for medical radiation, as the angle of incident radiations can affect the accuracy of the dose measurements. To ensure accurate in vivo dose measurements regardless of the angle of incidence, it is generally desirable for the dosimeters to have the least angular dependency [61]. In their work, Entezam et al. [62] examined the angular dependency of a 270 µm Ge-doped CF using ^{60}Co irradiations. The fibres were positioned at the isocentre of a Perspex phantom and irradiated with 9 different gantry angles. The results of their study indicated that the TL yield of the examined fibres was found to be independent of the irradiation angle. The authors also emphasized this characteristic as an advantage of silica fibres compared to diode, diamond, and MOSFET detectors.

Moradi et al. [34] conducted a comprehensive study on the angular dependency of silica fibre TL dosimeters using SMF dosimeters exposed to 30 kVp X-rays and 6 MV photons. The study assessed the response of the fibres in three placements, including free-in-air, on-surface, and in-depth, and also Monte Carlo simulations were performed to validate the experimental results. In contrast to Entezam et al., the findings of this experiment revealed a 35% angular dependency for 30 kVp photons when the dosimeters were placed in free air. The angular dependencies were lower for 6 MV, with values of 20%, 10%, and 3% for free-in-air, on-surface, and in-depth placements, respectively. The authors attributed these results to the secondary electron equilibrium inside the dosimeters. They concluded that these fibres could potentially be used for in-depth dosimetry in radiation therapy, suggesting that the use of tailor-made silica fibres instead of commercial SMFs may increase the core diameter of the fibres and improve their angular dependency.

Potential applications of silica fibres

The previous sections have discussed the potential applications of silica fibre TLDs in therapeutic and diagnostic radiation dosimetry. However, the remarkable dosimetric characteristics exhibited by these fibres may show additional prospects for their implementation in both medical and non-medical fields. This section will explore some practical applications of these dosimeters, focusing on their utilization in clinical trials and environmental dosimetry.

In vivo patient dosimetry

As previously noted, the primary objective of fabricating and characterizing silica fibre TLDs was to develop a novel category of TL dosimeters that could serve as an alternative to conventional TLDs, with improved performance. In addition to their excellent laboratory TL performance, several studies have also investigated the potential of these dosimeters in clinical trials. In a pioneering study, Moradi et al. [19] explored the potential of Ge-doped silica fibre TL dosimeters for measuring skin dose during intraoperative radiotherapy (IORT) for patients with breast cancer. The dosimeters were first characterized to evaluate their response to different beam qualities and dose rates, using an INTRABEAM® X-ray source with a nominal peak voltage of 50 kVp and a water phantom. The results were then validated using Gafchromic EBT3 film measurements and MCNPX Monte Carlo simulations. Regarding the clinical trial, the silica fibre TLDs were placed at four distinct locations on the skin of three patients' breasts to measure the dose during breast-conserving surgery and IORT. The authors reported that the skin dose in all three patients did not exceed the standard 6 Gy. Consequently, they concluded that with accurate consideration of correction factors (related to the applicator size) and the combined uncertainty (9.5–12.4%), these types of dosimeters can be utilized for in vivo dosimetry in the energy range of X-ray IORT.

In a study by Alyahyawi et al. [24], the performance of GeB-FF and TLD-100 dosimeters were compared in stereotactic radiosurgery (SRS) using a Gamma Knife as part of a safety audit. The dosimeters were placed on the skin of 20 different patients to calculate the scattered doses to the thyroid, chest, and pelvis during a brain radiosurgery treatment. The results showed acceptable consistency between the two dosimeters, with the uncorrected absorbed doses for GeB-FF being 1.4, 1.2, and 1.5 times higher than TLD-100 for the pelvis, chest, and neck, respectively. The differences were attributed to the energy-dependence TL response of silica-based media, which needs to be considered for calibrations. The authors concluded that silica fibre dosimeters were a possible candidate for in vivo skin dose calculations.

A rather similar study was conducted by Alyahyawi et al. [30] to evaluate the dose to the eye lens during the treatment planning stage (CT scanning) and high-energy SRS treatment at 20 radiotherapy centres in the UK. The study utilized an anthropomorphic head phantom and in vitro measurements were performed using commercial Ge-doped silica fibres, silica glass beads, and TLD-100. The dosimeters were characterized based on their energy and dose response, linearity, fading, and readout. Results showed that the measured doses by silica fibres and silica beads were almost twice the dose measured by TLD-100 for various imaging and therapeutic machines. This was stated to be attributed to the different spectrum of scattered radiations than the incident beam, which might have enhanced the photoelectric interactions in silica-based media. The audit results showed that the dose to the eye lens for all the centres was lower than 0.5 Gy for SRS treatment and ranged from around 0.03 to 0.08 Gy for CT scans. According to the authors of this study, using silica fibres is possible for eye-lens dosimetry. However, practical applications would require energy to be calibrated since these silica materials are not tissue-equivalent.

Targeted radionuclide therapy dosimetry

Targeted radionuclide therapy (TRT) is a cancer treatment modality that involves using radioactive isotopes coupled with targeting agents to eliminate cancer cells [68]. The technique has been used historically to treat various cancer types, including prostate cancer, neuroendocrine tumours, and lymphomas, using a variety of beta and alpha-emitting radionuclides, such as ^{131}I, ^{90}Y, ^{177}Lu, and ^{223}Ra. As one of the possible applications of silica fibre dosimeters, Bradley et al. [31] investigated the TL performance of Ge-doped SiO_2 optical fibres for in vitro measurement of alpha particles irradiated from ^{223}Ra. Six different types of fibres (Ge-CF, Ge-FF, Ge-PCF, Ge-PCFc, Ge-B-PCFc, and Ge-Br-PCFc) were irradiated by 60 kVp X-rays and also by 6.7 MeV alpha particles from ^{223}Ra. The TL responses were measured to evaluate the effectiveness of B and Br dopants in enhancing the sensitivity of silica fibres to X-ray and alpha radiations at a delivered dose of 50 Gy. The results showed that both dopants effectively increased the responses. Additionally, the TL responses for all the fibres were estimated to be approximately one order of magnitude higher than that of TLD-100. These findings further support the previously discussed outcomes and indicate the potential application of silica fibres in this field.

Dose mapping in ^{60}Co gamma-ray irradiator

Gamma irradiation facilities are broadly used for a variety of applications, including food irradiation, material examination, radiobiology and medical research, and sterilization. The type of radiation source and also the chamber geometry will determine the dose inhomogeneity inside the chamber [69]. Prior to sample irradiation and to ensure the delivery of accurate doses to the targets, it is important to evaluate the dose distribution inside the irradiation chamber. Using silica fibre dosimeters, Moradi et al. [70] performed experiments to study the dose distribution inside a Gammacell-220 (GC-220) machine's chamber. The device contains a ^{60}Co source inside a cylindrical chamber and can be used for radiation research in different fields. In their study, a total number of 100 SMF dosimeters were irradiated by gamma rays up to about 1 Gy dose. The fibres were carefully placed inside the chamber to verify the radial and axial deviations in the delivered dose, along with the dose rate on the chamber's lowest surface. The results were then compared to Monte Carlo simulations, and a good agreement between the experiment and simulation results was reported. The dose rates on the centre and along the vertical axis were compared to the maximum dose rate, exhibiting a reduction of 22% and 26% at the lower and upper points, respectively. The authors then concluded that the silica fibre TLDs could provide greater accuracy in comparison with previously reported results in the literature.

Environmental monitoring

Due to the adverse health-related effects of environmental radiation from natural sources, monitoring the dose levels is essential for protecting public health and ensuring that radiation exposure is within the safe limits recommended by various regulatory bodies. Whereas conventional TLDs are widely being used for environmental monitoring, some challenges such as limited sensitivity and also their hygroscopic nature may restrict their functionality. The capability of two types of silica fibres (PCFc-Ge and PCFc-Ge–B, 8 mol%) in environmental gamma-ray dose measurement was assessed by Rozaila et al. [71]. The results were compared with two commercial TLDs (TLD-100 and TLD-200) and also bulk measurements by an HPGe gamma-ray spectrometer. Initially, the lab measurements were conducted using an X-ray source with $E_{mean} \sim 40$ keV for doses from 0.5 to 10 mGy, and glow curves and signal fading (up to 35 days post-irradiation) were measured. For the on-site measurements, the samples were buried at 8 different locations of the Gebeng Industrial Estate (GIE) in Pahang state, Malaysia, for between 2 and 8 months. According to their findings, PCFc-Ge had the best performance among all four types, which was however different from their lab calibrations where TLD-200 showed superiority. While the commercial TLDs suffered from degradation due to humidity, the TL response of all samples increased for 2–4 months of sample burial and diminished by increasing the burial duration to 6–8 months. The doses measured by all the TLD materials were significantly lower than those of gamma-ray spectroscopy (up to 50% for PCFc-Ge). However, the overall performance of silica-based dosimeters has shown promise for their application in environmental radiation monitoring.

Conclusion

Since the emergence of silica fibre dosimeters, extensive experimental and simulation studies have investigated their characteristics, capabilities, and limitations over the past two decades. In this review, we analyzed the data from recent literature, focusing on the TL performance and medical applications of silica fibre TL dosimeters.

Regarding fibre structure, different types of fibres have shown varied performance. Photonic crystal fibre (PCF) dosimeters have exhibited superior TL performance, and doped fibres have demonstrated higher sensitivity and more acceptable TL response than un-doped ones. While a majority of the literature used germanium (Ge) as the dopant, further research is needed to explore other dopant materials and optimize dopant concentrations for various applications. The substantial enhancement of TL performance through collapsing the capillary fibres is widely recognized. This technique can also be applied to PCFs, as collapsed PCF dosimeters have demonstrated significantly higher sensitivities compared to un-collapsed ones, as well as conventional TLD-100.

The majority of research has concentrated on the dosimetry of high-energy photons and electrons using silica fibres, but more extensive investigations are required to study their behaviour in a broader radiation energy and dose range, including ultra-high doses in FLASH radiotherapy and other radiotherapy techniques like hadron and heavy ion therapy. However, clinical trials and environmental monitoring experiments have indicated the potential capability of silica fibre dosimeters in these fields.

Silica fibre dosimeters offer many advantages, including high spatial resolution, sensitivity, water resistance, and insensitivity to electromagnetic fields, making them ideal for medical applications and technically comparable to conventional TLDs. However, challenges remain, such as the uncertified linearity in low-energy radiations and relatively high signal fading, which limits the time between irradiation and readout. Moreover, the high Z_{eff} of silica fibres makes them non-soft-tissue equivalent, demanding accurate correction factors for different applications. Further research on the stability of fibres in harsh environments is also required for their clinical utilization. With future research addressing these limitations, the commercial production and application of silica fibre TL dosimeters in medical radiation dosimetry are expected in the near future.

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