Radiation Physics and Chemistry 166 (2020) 108487

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Advanced thermoluminescence dosimetric characterization of fabricated Ge-Doped optical fibres (FGDOFs) for electron beams dosimetry

Z. Zakaria[a,b], M.Z. Abdul Aziz[c], N.H. Ishak[c], S. Suppiah[a,d], D.A. Bradley[e,f], N. Mohd Noor[a,*]

[a] Department of Imaging, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia
[b] Oncological and Radiological Sciences Cluster, Advanced Medical and Dental Institute (AMDI), Universiti Sains Malaysia (USM), 13200, Bertam, Penang, Malaysia
[c] Universiti Kuala Lumpur British Malaysian Institute (UniKL BMI), Bt 8 Jalan Sg Pusu, 53100, Gombak, Selangor, Malaysia
[d] Centre for Diagnostic Nuclear Imaging, UPM, 4300, Serdang, Selangor, Malaysia
[e] Sunway University Centre for Biomedical Physics, Jalan Universiti, 46150, Petaling Jaya, Selangor, Malaysia
[f] Centre for Nuclear and Radiation Physics, Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom

ARTICLE INFO

Keywords:
Dose linearity
Optical fibres
Sensitivity
Thermoluminescence

ABSTRACT

For fabricated Ge-doped optical fibres (FGDOFs) investigation is made of a range of optical fibre thermoluminescence (TL) characteristics: sensitivity, dose linearity, dose rate dependence and fading together with exploration also made of percentage depth dose (PDD) curves for electron beams dosimetry. The fibres used were of various shapes, cross-section dimensions and germanium (Ge) concentrations. The responses of FGDOFs were compared against commercial fibres as well as that of an ionization chamber (PTW 31010 Semiflex 31010) and Gafchromic™ EBT3 films. All fibres were irradiated at the Royal Surrey County Hospital (UK) using 6-, 9- and 12 MeV electron energies, with 100 cm focus-to-sample distance (FSD) and $10 \times 10\,cm^2$ field size, measurements being made up to the depth of dose maximum, Z_{max}. At a fixed 9 MeV electron energy, dose rates from 100 up to 600 cGy/min were used with field sizes ranging from $6 \times 6\,cm^2$ to $25 \times 25\,cm^2$. For PDD curves, the fibres were placed at depths from 0 cm to 6 cm, comparison being made against the ionization chamber and films. The water-to-air stopping power ratios and the fluence correction factors, P_{fl} were required in determining PDD curves when using the ionization chamber. TL yields against dose were highly linear ($R^2 > 0.99$). A low dependence on dose rate was found for all fibres. The 2.3 mol% flat fibre (FF) produced the superior performance, with the highest sensitivity, minimum TL fading for up to 3 months as well as relative difference of less than 2% for the build-up and fall-off region for PDD curves.

1. Introduction

Over the past five years, for photons, protons and gammas beam dosimetry the characteristics of fabricated Ge-doped optical fibres (FGDOFs) have been extensively investigated by a number of researchers. Notably, for photon beams investigation of the characteristics of FGDOFs included their application in numerous fields such as in a postal radiotherapy dose audit (Fadzil et al., 2014), patient dose measurement in x-ray diagnostic procedures (Ramli et al., 2015) and small fields dosimetry (Lam et al., 2019). Along similar lines, the characteristics of FGDOFs were also investigated in proton beams measurement (Hassan et al., 2017) as well as in gamma irradiation for food irradiation dosimetry (Noor et al., 2015) and thermoluminescence response of Ge-doped flat fibres (Nawi et al., 2015). Present interest concerns the incredible advances made in recent years in the technology of radiotherapy delivery, associated advances being needed in dosimetric capability in order to support and widen the application boundaries. In particular for electron beams such as those produced in use of the so-called FLASH technology (see for instance Durante et al., 2018), generating high intensity beams for radiotherapy, development and characterization of FGDOF dosimetry is thought to have a promising role.

With the advent of linacs, electron beams have become a popular choice in the treatment of superficial tumours, offering minimized radiation dose to the healthy at-depth tissues. In general, the dose delivered to specific depths in water is well-indicated by the shape of central axis depth dose, also known as the percentage depth dose (PDD) curve. Current dosimetry technology in high energy electron beam radiotherapy treatment requires the dosimeters to be energy independent as well as of small volume and radiation hard (Venanzio et al., 2015). Nowadays, a number of dosimetric systems are available for use in electron beams dosimetry, ionization chambers (IC), film of

* Corresponding author.
E-mail address: noramaliza@upm.edu.my (N.M. Noor).

https://doi.org/10.1016/j.radphyschem.2019.108487
Received 31 May 2019; Received in revised form 4 September 2019; Accepted 6 September 2019
Available online 07 September 2019
0969-806X/

various types, TLDs and MOSFETs included. Of these, the IC is universally considered the gold-standard dosimeter in providing accurate evaluation of dose. However, the use of the IC in PDD measurement is undoubtedly challenging, account being needed of depth ionization-to-dose conversion factors, stopping power ratios, perturbation factors as well as correction factors such as polarity effects and ion recombination. Amin et al. (2011) studied the accuracy of small fields of electron beams by using a high-sensitivity microMOSFET detector. Some of the factors that contributed to the limitation of this study were the location of the depth of dose maximum, Z_{max} in percentage depth dose (PDD) curves and positioning of the ionization chamber in the electron beam. Herein, interest is in a TL system offering unusually fine spatial resolution, namely the Ge-doped silica fibres, of which earlier versions have been reviewed above. In conjunction with the evaluation of novel FGDOFs for clinical electron radiotherapy applications, an initial requirement is for their TL characteristics to be established. This is the present objective, fundamental and applied characterisations of FGDOFs for high-energy electron therapy.

2. Materials and methods

2.1. Fabrication of FGDOFs

The present work used various structures and compositions of FGDOFs by means of different shapes (flat and cylindrical), amount of germanium dopant concentrations (2.3% and 6.0% mol) and dimension/diameter. Indeed, all of these FGDOFs were fabricated through use of the Modified Chemical Vapour Deposition (MCVD) and fibre pulling techniques as detailed in Noor et al. (2016a,b) and Bradley et al. (2017). The FGDOFs used in this study were flat fibre (FF) with 2.3% mol germanium dopant and dimensions 643 µm × 356 µm (2.3% mol; 643 µm × 356 µm) and 6.0% mol germanium dopant and dimensions 620 µm × 165 µm (6.0% mol; 620 µm × 165 µm) while the cylindrical fibres (CF) studied were: 2.3% mol germanium dopant and diameter 481 µm (2.3% mol; 481 µm); 6.0% mol germanium dopant and diameter 486 µm (6.0% mol; 486 µm) and; 6.0% mol germanium dopant and diameter 616 µm (6.0% mol; 616 µm).

2.2. Preparation of FGDOFs, commercial optical fibres and Gafchromic™ EBT3 films

The preparation of all FGDOFs and commercial fibres for cutting and the annealing process has been carried out as detailed in Noor et al. (2016a,b). For proper fibre arrangements, they were grouped and encapsulated in plastic capsules. To compare the PDD characteristic, Gafchromic™ EBT3 film of dimensions 20.3 cm × 25.4 cm (8" × 10") (Huet et al., 2012) was used. This high spatial resolution film is composed of a single active component layer, nominally 27 µm thick, marker dye, stabilizers and other additives offering the film extremely low energy dependence. The films were placed in reduced light conditions and were initially inspected to ensure freedom from dust, scratches and fingerprints.

2.3. General setup for electron irradiation of fabricated germanium (Ge) doped cylindrical optical fibres

In electron linac irradiations, the FGDOFs were exposed at 100 cm focus-to-surface (FSD) with a field size of 10 cm × 10 cm at a dose rate of 600 cGy/min at Z_{max}. The electron beam energies used were 6-, 9- and 12 MeV, doses ranging from 1 Gy up to 5 Gy. The fibres were sandwiched with 1 cm bolus and *solid water*™ phantom (30 cm × 30 cm × 15 cm) to create the build-up thickness and full scatter conditions. The dose sensitivity and linearity, dose rate and signal fading characteristics were investigated by primary fibre irradiations using an Elekta Synergy® linear accelerator (Linac) located at the Royal Surrey County Hospital (UK). Comparison measurements were also made, investigating commercially available optical fibres. The depth-dose distribution evaluations were made at the Radiotherapy Unit, Advanced Medical and Dental Institute (AMDI), Bertam, Pulau Pinang (Malaysia).

2.4. Basic characteristics of FGDOFs

2.4.1. Dose sensitivity and linearity

TL dose sensitivity and signal linearity of the fibres were made using 6-, 9- and 12 MeV electron energy, over a dose range 1 Gy up to 5 Gy.

2.4.2. Dose rate dependence

The fibres were exposed at dose rates ranging from 100 up to 600 cGy/min.

2.4.3. TL signal fading

To determine the TL fading, the FGDOFs were exposed to a fixed dose of 2 Gy at 9 MeV electron energy. Post-irradiation, the fibres were stored in a light-tight box to minimize release of trapped electrons contributing to signal loss. The readout processes were assessed for periods of 5, 13, 147, 198 and 204 days.

2.5. Advanced characteristics of FGDOFs; percentage depth dose (PDD)

To establish the PDD curve, the FGDOFs were arranged in three columns parallel to each other with different depths from 0 cm up to 6 cm on 4 cm × 10 cm cardboard. Laterally, the FGDOFs were sandwiched between layers of *solid water*™ phantom and bolus, keeping the focus-to-surface distance (FSD) at 100 cm as shown in Fig. 1. The PDD responses were determined for 9 MeV electron beams angles normal to the Linac head and phantom. The field size used was at a nominal 10 cm × 10 cm. The same set-up was adopted in a separate and subsequent procedure making use of Gafchromic™ EBT3 film. The irradiated and unirradiated films were scanned and analysed using an EPSON scanner and ImageJ software. PDD results were expressed as the ratio between the response from the samples and the reading obtained at Z_{max}. The PDD results from the FGDOFs were then compared against the corresponding PDD values measured using the IC and Gafchromic™ EBT3 film.

2.6. Readout measurement

Table 1 displays the glow curve Time-Temperature Profile (TTP) parameters used for each group of FGDOFs, determined to provide optimum readout measurements. In the Table, groups i to v respectively represent: FF (2.3% mol; 643 µm × 356 µm); FF (6.0% mol; 620 µm × 165 µm); CF (2.3% mol; 481 µm); CF (6.0% mol; 486 µm) and; CF (6.0% mol; 616 µm).

2.7. Statistical analysis

The software SPPS Version 24 and the One-Way ANOVA statistical test were used for all analyses in this study.

3. Results and discussion

3.1. Sensitivity

Figs. 2–4 show the sensitivity (normalized TL yield) versus dose results obtained for the various FGDOFs and commercial optical fibres for electron energies 6-, 9- and 12 MeV. Both flat fibres types [FF (2.3% mol; 643 µm × 356 µm) and FF (6.0% mol; 620 µm × 165 µm)] are identified to offer greatly superior (by a factor of 2) sensitivity when compared against the cylindrical FGDOFs and commercial fibres for all three electron energies. Prior investigations, predominantly using linac x-rays, have obtained similar higher sensitivity results for the flat fibres,

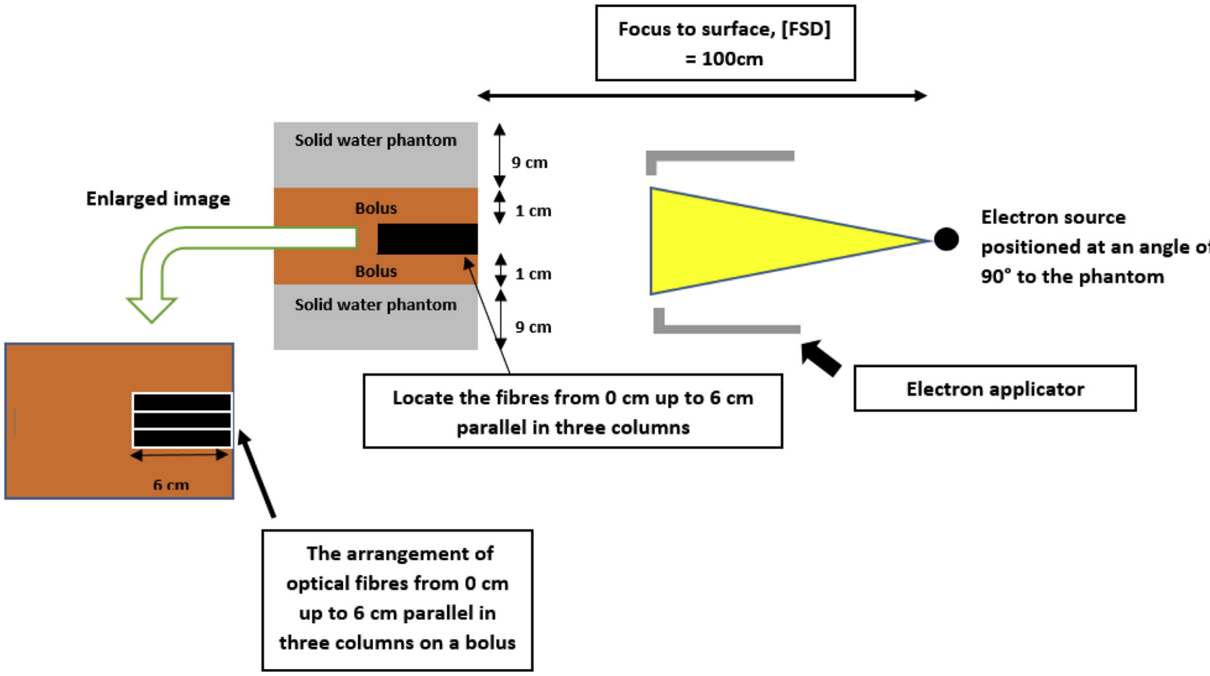

Fig. 1. Schematic diagram of set-up for PDD experiment.

Table 1
Time-Temperature profile (TTP) for FGDOFs readout measurement.

Parameters	FGDOFs group				
	i	ii	iii	iv	v
1) Preheat: Temperature	110 °C	80 °C	100 °C	70 °C	80 °C
Time			10 s		
2) Acquire: Maximum temperature			400 °C		
Temperature/heating rate			30 °C/s		
Time			16 2/3 s		
3) Anneal: Temperature			400 °C		
Time			10 s		

demonstrated to be due to their collapsed surface structures, introducing additional defect sites (Ghomeishi et al., 2015; Fadzil et al., 2018). In this it is seen that with the greater the number of defect sites (predominantly deep traps resulting from the collapsing down event), the greater the number of electron-hole trappings that occur during the irradiation process, producing enhanced sensitivity compared to the cylindrical fibres.

3.2. Dose linearity

Fig. 5 shows excellent linearity of TL signal across the applied 1–5 Gy dose range for the 9 MeV electron energy investigated, with coefficients of determination (R^2) from 0.95 to 0.99 for FGDOFs compared to commercial fibres at 0.93. In line with expectation, all FGDOFs show increase in TL with increasing radiation dose, as also shown in other work (Fadzil et al., 2014; Hassan et al., 2017) for proton and gamma beam irradiations respectively.

3.3. Dose rate dependence

Dependence on dose rates from 100 to 600 cGy/min (400 cGy being a typical value used in teletherapy) are exemplified for the various FGDOFs and commercial cylindrical fibre in Fig. 6 for 9 MeV electrons,

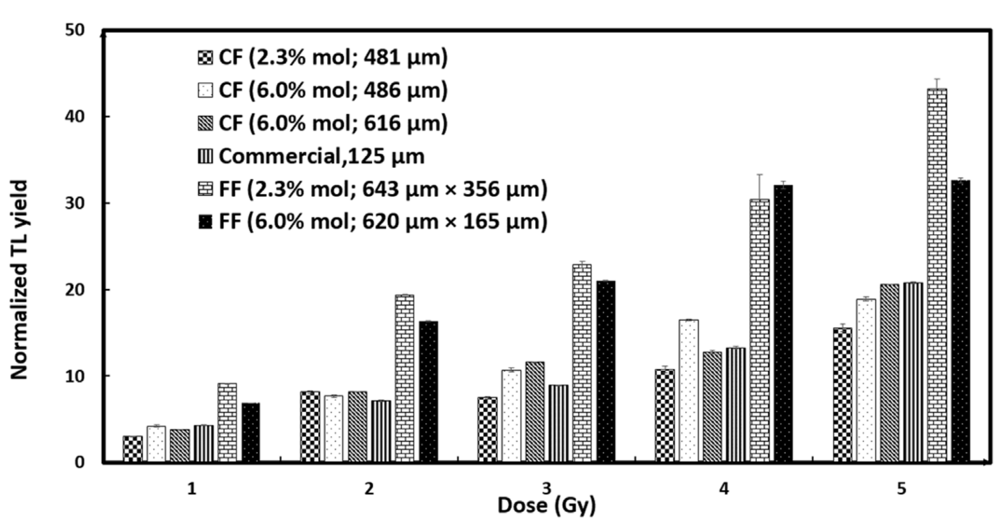

Fig. 2. The sensitivity of FGDOFs and commercial optical fibres for 6 MeV electrons.

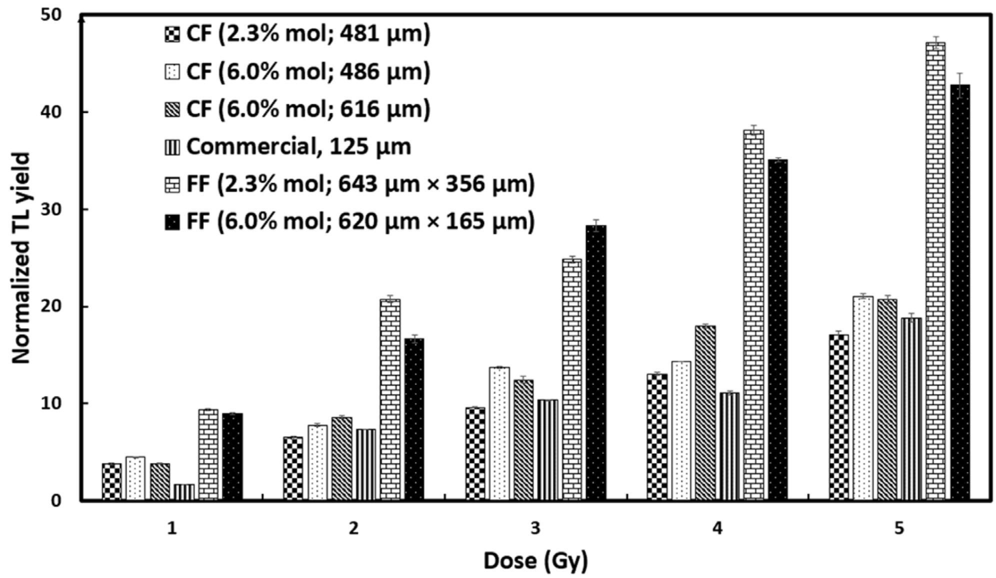

Fig. 3. The sensitivity of FGDOFs and commercial optical fibres for 9 MeV electrons.

being similar to the result shown by Abdul Rahman et al. (2011) for commercial fibres for 9 MeV electrons. The findings are significantly different at $p < 0.05$ with 95% confidence level. Of note is the relatively flat dose-rate response for the FF (6.0% mol; 620 µm × 165 µm) dosimeter, potentially of interest for FLASH electron therapy dosimetry.

3.4. TL signal fading

Fig. 7 (a) to 7 (f) display TL signal fading results for 9 MeV irradiated FGDOFs and commercial optical fibres, normalized to day-five post-irradiation. From these figures, a steady decline is observed from day 5 up to day 204. The minimum signal fading is found to be approximately 15% for the 2.3 mol% flat fibre (FF) [643 × 356 μm^2] evaluated up to day 204 followed by 24%, 26%, 33%, 37% and 47% for commercial optical fibre, 2.3 mol% cylindrical fibre (CF) (481 µm), 6.0 mol% CF (486 µm), 6.0 mol% FF (620 × 165 μm^2) and 6.0 mol% CF (616 µm) respectively. Previous study of the 2.3 mol% FF dosimeters in proton beam measurements using an 150 MeV energy at a dose of 5 Gy showed a TL signal loss of 24% 96 days post-irradiation (Hassan et al., 2017).

3.5. Percentage depth dose (PDD)

Fig. 8 shows the PDD curve for 9 MeV electrons in terms of the build-up and fall-off region for all of the investigated FGDOFs, the PTW 31010 IC and Gafchromic™ EBT3 film. All are plotted together to provide for comparison. The results for the FGDOFs offer excellent comparison with the reference curve provided by the IC. For the build-up and fall-off region, no significant difference is found at $p > 0.05$ between the FGDOFs findings and ionization chamber results. The flat response shown in Fig. 9 further supports the findings. Less favourable results are obtained using Gafchromic™ EBT3 film in the build-up region. For all dosimeters this results in higher surface dose and more rapid build-up over to the dose maximum, Z_{max}. As shown in Fig. 8, beyond Z_{max} the so-called fall-off region occurs, attenuation dominating over electron forward scatter. The dependence on electron energy and density of the attenuating medium contribute to the rate of energy loss from collisional interactions (Podgorsak, 2005). Beyond the fall-off region the contribution from bremsstrahlung contamination is less than 3%. For all of the investigated FGDOFs and Gafchromic™ EBT3 film the mean differences from the IC value for the PDD at the surface (0 cm) has been measured to be within a tolerance of ± 1.0%, as shown in Table 2.

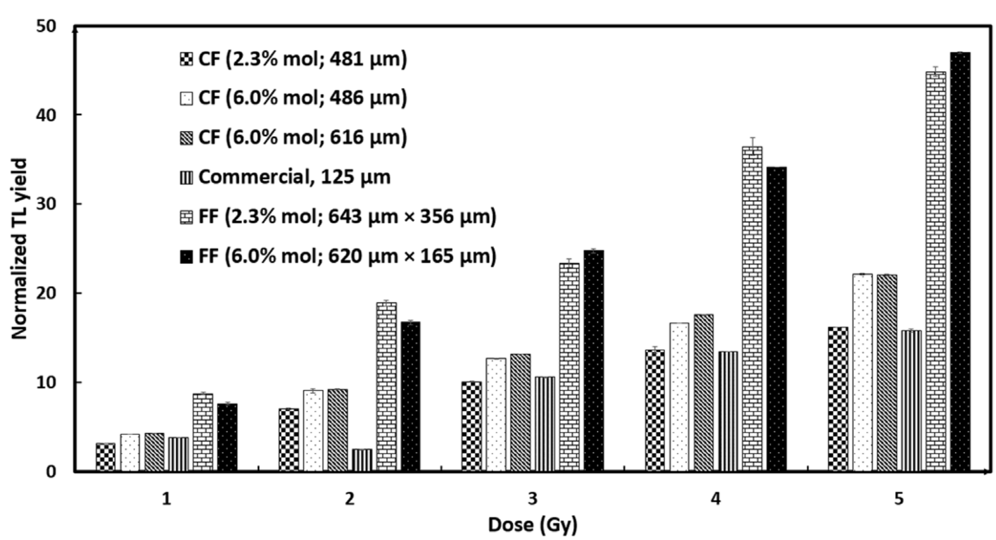

Fig. 4. The sensitivity of FGDOFs and commercial optical fibres for 12 MeV electrons.

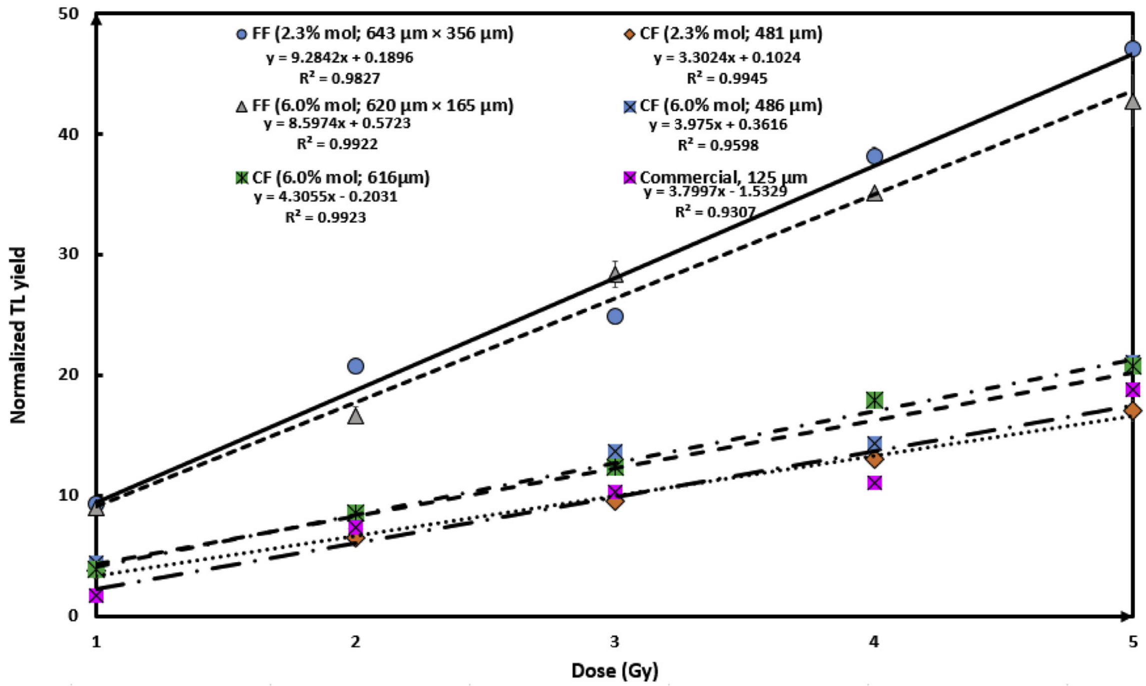

Fig. 5. TL normalized over doses for FGDOFs and commercial fibre for 9 MeV.

In regard to the results presented in Fig. 9, showing relative differences between a range of pairings of dosimeters, two particular dosimeter pairings have shown the least and greatest relative differences from IC results within the build-up region, at less than 2% and 6% respectively for the IC and 2.3% mol Ge (643 μm × 356 μm) and the IC with the Gafchromic™ EBT3 film.

4. Conclusions

The investigations herein concern electron beam dosimetry, evaluated using various forms of Ge-doped fibres that have been shown at radiotherapy doses to yield appreciable thermoluminescence The two flat fibre forms (2.3% and 6.0% mol Ge) show greater sensitivity compared to the cylindrical fibres, due to the additional defects created through strain in the collapsing down process. All of the FGDOFs are seen to provide excellent linearity, with a coefficient of determination (R^2) from 0.95 to 0.99 over the investigated dose range 1 Gy up to 5 Gy as well as minimal fading compared to the commercial fibres. For PDD measurements, it is shown that the relative difference within the build-up region is better than 2.0% between FGDOFs and the reference ionization chamber. FGDOFs can easily be handled, positioned and overcome some of the limitations contributed by other dosimeters in electron beams dosimetry. As a final conclusion, FGDOFs offer a system of dosimetry of considerable spatial resolution and of low dose-rate dependency in pursuit of clinical applications for electron beam dosimetry. Thus said, the fibres dose rate correction factor will need to be considered in establishing their use for absorbed dose calculations in higher dose rate electron beam delivery such as that of FLASH.

Acknowledgement

The authors are indebted to Universiti Putra Malaysia (UPM) for

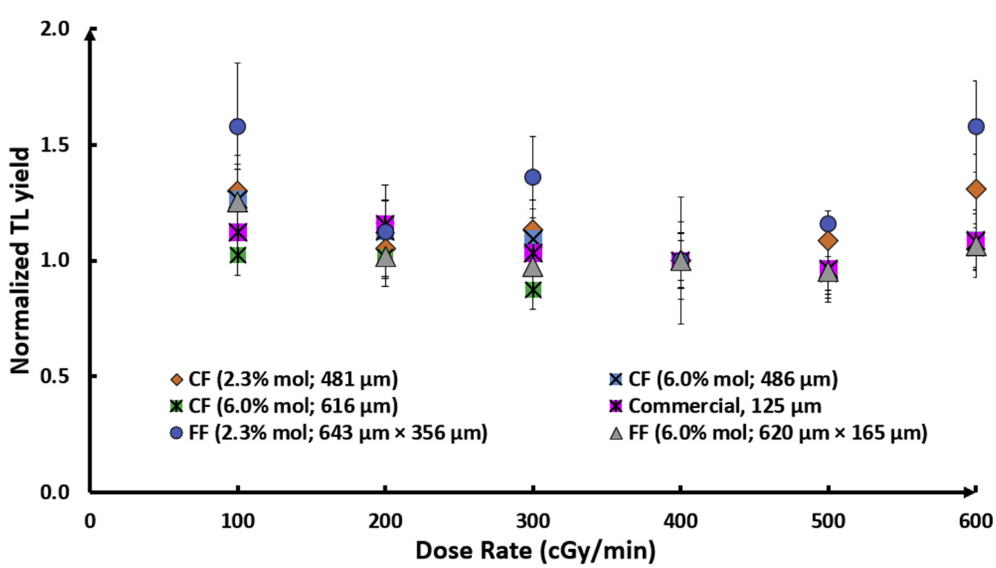

Fig. 6. TL normalized over doses rate for FGDOFs and commercial optical fibre for 9 MeV.

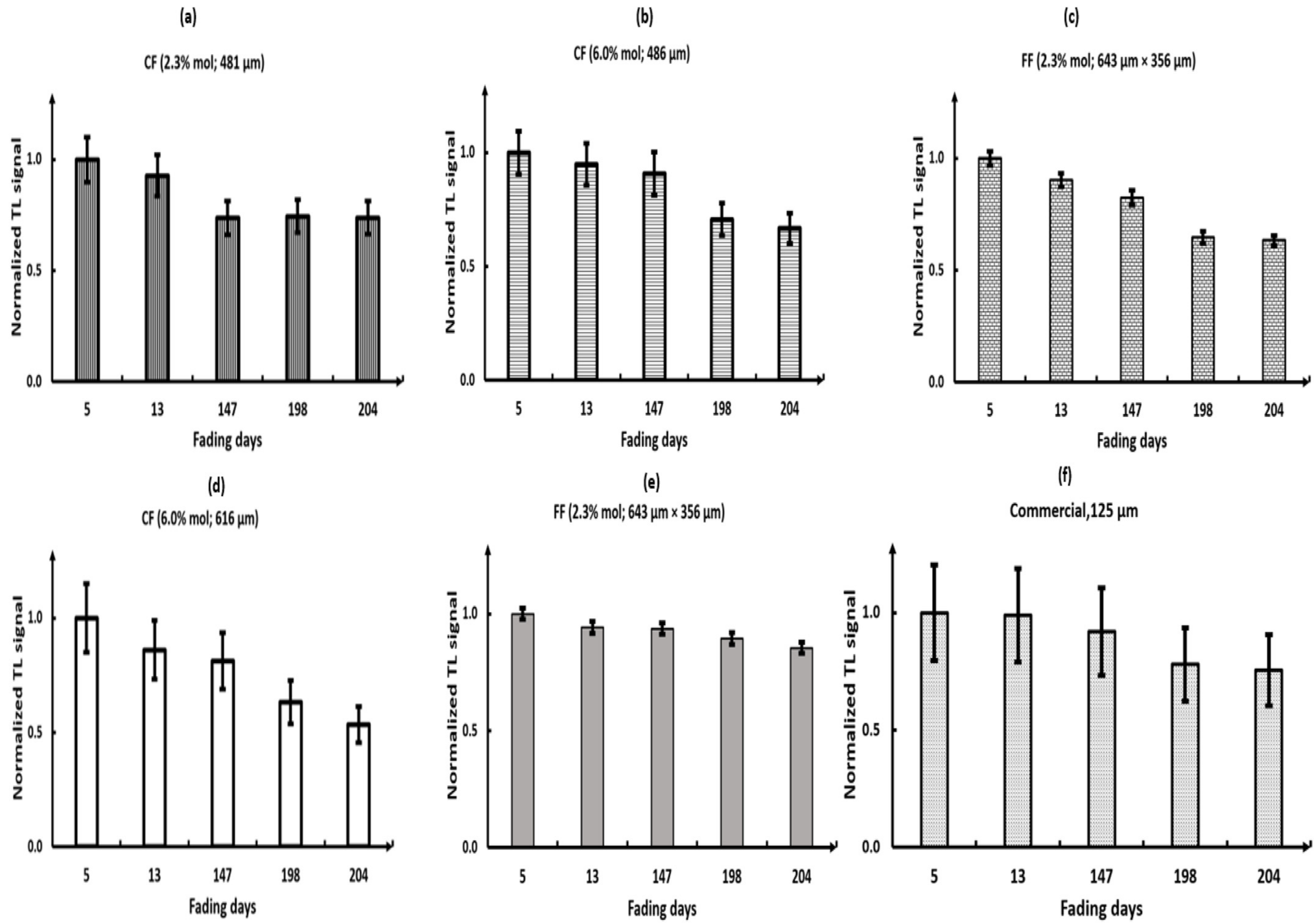

Fig. 7. TL normalized versus post-irradiation days for 9 MeV electron beam irradiated fibres, as follows: a) 2.3% mol Ge, 481 µm; b) 6.0% mol Ge, 486 µm); c) 6.0% mol Ge; 620 × 165 µm); d) 6.0% mol Ge; 616 µm; e) 6.0% mol Ge; 643 × 356 µm); f) commercial, 125 µm.

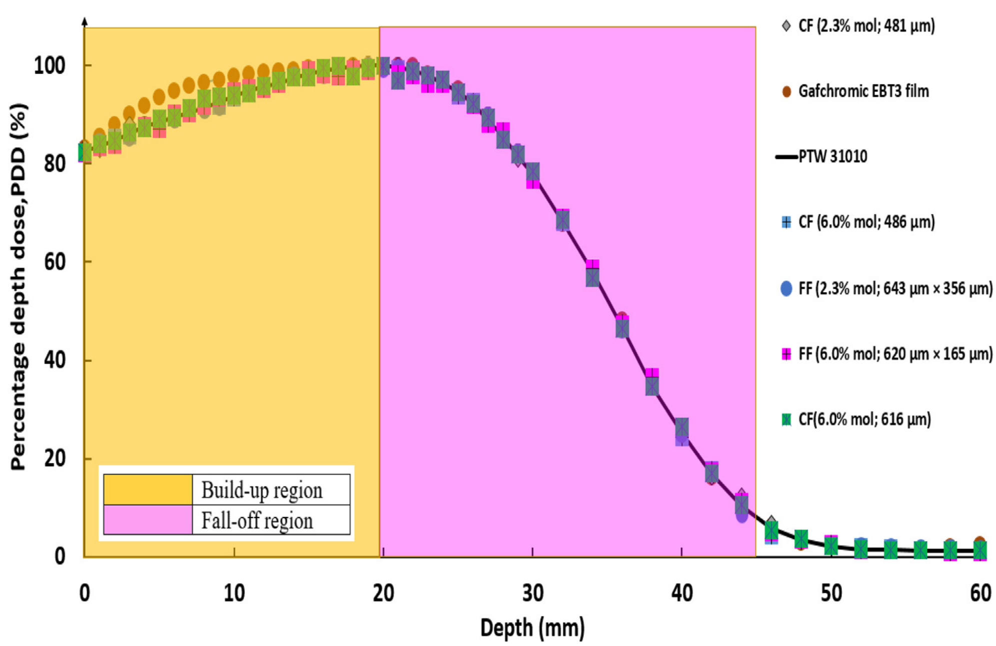

Fig. 8. PDD of PTW 31010 IC, all fabricated fibres & Gafchromic™ EBT3 film at different depths.

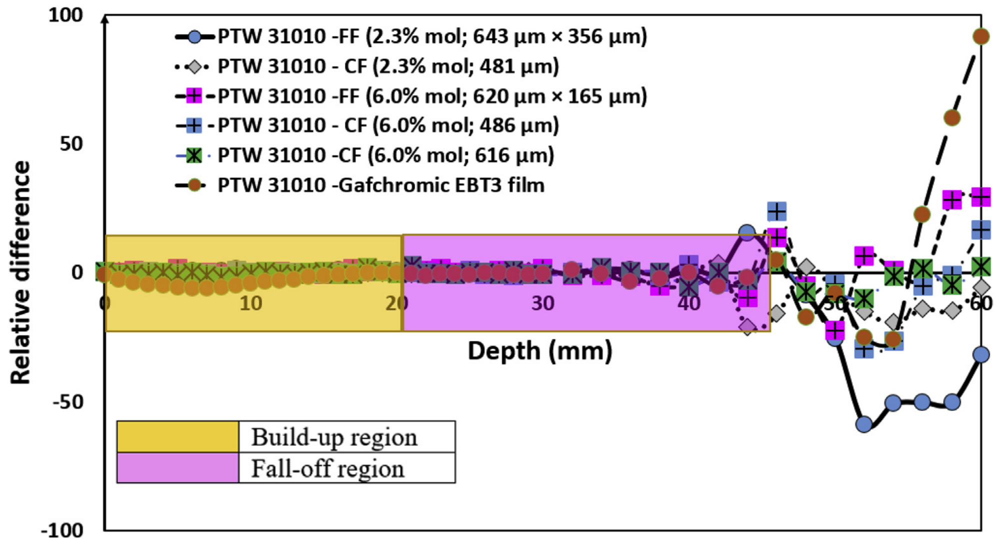

Fig. 9. Relative difference between six dosimeter pairings: IC and 2.3% mol Ge; 643 µm × 356 µm; IC and 2.3% mol Ge; 481 µm); IC and 6.0% mol Ge; 620 µm × 165 µm; IC and 6.0% mol Ge; 486 µm); IC and 6.0% mol Ge, 616 µm and; IC and Gafchromic™ EBT3 film.

Table 2
Mean difference of FGDOFs and film at the surface against PTW 31010.

Types of dosimeter	PDD at the surface (%)	Mean difference
1. FF (2.3% mol; 643 µm × 356 µm)	82.7	0.1
2. CF (2.3% mol; 481 µm)	83.3	0.8
3. FF (6.0% mol; 620 µm × 165 µm)	82.2	−0.5
4. CF (6.0% mol; 486 µm)	82.2	0.5
5. CF (6.0% mol; 616 µm)	82.3	−0.4
6. Gafchromic™ EBT3 film	83.2	0.8

providing financial support for the conduct of the experiment through Putra grants (project no: 9615500), also that from the Fundamental Research Grant Scheme (FRGS) from the Malaysian Ministry of Higher Education (project no: 554012). We also offer appreciation to the staff at the Royal Surrey County Hospital and AMDI, Bertam, Penang for allowing us to make use of their facilities during the irradiations procedures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.radphyschem.2019.108487.

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