Dosimetric characteristics of fabricated germanium doped optical fibres for a postal audit of therapy electron beams

N Abdullah[1,2], D.A. Bradley[3,4], A. Nisbet[5], Z Kamarul Zaman[6], S S Deraman[2], N Mohd Noor[1,7]

[1]*Department of Radiology, Faculty of Medicine and Health Sciences, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[2]*Radiation Metrology Group, Malaysian Nuclear Agency, 43000 Kajang, Selangor, Malaysia*
[3]*Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[4]*Sunway University, Centre for Applied Physics and Radiation Technologies, Jalan Universiti, 46150 Petaling Jaya, Malaysia*
[5]*Department of Medical Physics and Biomedical Engineering, Faculty of Engineering Science, University College London, England*
[6]*Department of Medical Physics, University of Malaya Medical Centre, 59100 Kuala Lumpur, Malaysia*
[7]*Medical Physics Unit, Teaching Hospital Universiti Putra Malaysia, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*

Corresponding author: noramaliza@upm.edu.my

ABSTRACT
The dosimetric characteristics of germanium (Ge) doped optical fibres are investigated as a potential dosimetric alternative for electron beam therapy postal audits. The dosimetric characteristics of 6 mol% Ge-doped optical fibres fabricated as cylindrical fibres (CF) and flat fibres (FF) are established in terms of signal fading, linearity of dose-response, beam energy- and dose rate dependence. Pilot electron beam therapy audit study irradiations are made with a linear accelerator located at the Royal Surrey County Hospital, applying International Atomic Energy Agency (IAEA) standard irradiation procedures for reference and non-reference conditions. Results for the CF and FF show fading of 26% and 20% respectively at 120 days post-irradiation. For a 6 MeV electron beam the dose-response is observed to be linear over the dose range 1 to 3 Gy, the least determination coefficient, R^2, being 0.985. The results of the electron beam therapy audit are within the tolerance limit of 5% recommended by the International Commission on Radiation Units and Measurements (ICRU) Report No. 24, with a maximum deviation of 4% for FF at a 6 MeV electron beam under non-reference conditions. In conclusion, the fabricated Ge-doped optical fibres are seen to offer suitability for use as an alternative dosimeter to TLD-100 in electron beam therapy postal audit.

Keywords: Fabricated Ge-doped optical fibres; electron beam therapy audit; reference and non-reference conditions

1. Introduction

The postal dosimetry audit is a well-accepted part of an overall radiotherapy quality assurance programme, in good part to verify accuracy of dosimetry measurements; the International Commission on Radiation Units and Measurements (ICRU) Report 24 recommends a limit on tolerance of 5% at the 95% confidence level (ICRU, 1976). In radiotherapy, under- or overdose is clearly to be avoided, with potential for impact on the effectiveness of cancer treatment and the likelihood of radiation injury to patients (Healy et al., 2020; Kry et al., 2018; van der Merwe et al., 2017). The postal dosimetry audit also forms an essential control indicator of the competency of the in-service physicists, with traceability of measurements provided by national dosimetry laboratories (Podgorsak, 2005). A good number of national institutes provide postal dosimetry audit services to radiotherapy centres, including dosimetry audits of irradiations made under reference and non-reference conditions (Da Rosa et al., 2008; Kroutilíková et al., 2003; Rahman et al., 2008), on-site visit audits (de Prez et al., 2018; Lye et al., 2019; Park et al., 2017), and more complex issues such as treatment planning system audits (Okamoto et al., 2018; Rutonjski et al., 2012) and *in-vivo* dosimetry audits (Kamomae et al. 2017). For radiotherapy centres in IAEA member states, the International Atomic Energy Agency (IAEA) in collaboration with the World Health Organisation (WHO) offers an important role of conducting a postal dosimetry audit based on use of mailed thermoluminescence dosimeters (TLD). To-date this has focused most particularly on reference condition for high energy photon beams, with more than 50 years of experience accrued (Izewska et al., 2020).

There are many approaches to the dosimetry audit that are being practised at national and regional level worldwide. For instance, within the United Kingdom (UK), the audits cover various levels from basic reference dosimetry to advanced radiotherapy techniques (Clark et al., 2015). In the reference dosimetry audit, the accuracy of absolute dose calibrations for megavoltage photon beams, electron beams and kilovoltage X-ray beams are verified following the relevant UK Code of Practise (CoP) (Thomas et al., 2017). For advanced radiotherapy techniques involved validation of treatment delivery from total skin electron beam therapy (TSEBT) (Misson-Yates et al., 2015), Intensity-Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) (Tsang et al., 2017) and brachytherapy system (Humbert-Vidan et al., 2017).

In regard to audit methodologies, the IAEA has introduced nine steps, focusing more so on photon beam audits. These involve beam output measurement with various irradiation setups (steps 1-3) to more complex arrangements (steps 4-6) and advanced radiotherapy treatments (steps 7-9) involving intensity modulated radiotherapy (IMRT) (Wesolowska et al., 2019), treatment planning systems (TPS) and small field beams (Lechner et al., 2018). However, with more than 50 years of expertise, the IAEA has mostly concentrated on the step 1 audit of reference conditions for high-energy photon beams with participation of IAEA member states (Izewska et al., 2020b). It is estimated that the dosimetry audit covers slightly more than 10% of the needs (Izewska et al., 2018). This is certainly to be considered insufficient. Therefore, national remote dosimetry audits should be established with the aim of catering to all nine steps of audit methodologies for all radiotherapy centres.

As a member state of the IAEA/WHO Network of Secondary Standard Dosimetry Laboratories (SSDLs), over the past 36 years Malaysia has participated in the IAEA/WHO TLD Postal Dose Quality Audit Service (Abdullah & Dolah, 2021; Samat et al., 2009). In 2011 the IAEA designated the Malaysian SSDL a moderator in coordinating the IAEA/WHO TLD Postal Dose Quality Audit Service for radiotherapy centres within Malaysia (Noor et al., 2017; Abdullah et al., 2018). Malaysia has also conducted national postal dosimetry audits for reference condition dosimetry for high energy photon beams based on IAEA Technical Report Series (TRS) No. 277 (Rassiah et al., 2004) and TRS No. 398 (Noor et al., 2014; Abdullah et al., 2016). The national dosimetry audit has subsequently been extended to include high energy photon beams non-reference conditions (Ahmad Fadzil, 2020) and intensity-modulated radiotherapy (IMRT) involving treatment planning and on-site audits (Diyana et al., 2020).

In recent years other than TLD-100, various types of transfer detector have also been introduced in postal dosimetry audits, including RPL (radio-photoluminescence) glass dosimeters (Mizuno et al., 2014; Okamoto et al., 2018), optically stimulated luminescent (OSL) dosimeters (Alvarez et al., 2017; Lye et al., 2014), radio-chromic film (Okamoto et al., 2018) and alanine dosimeters (McEwen et al., 2015; Yamaguchi et al., 2020). A number of workers have examined the feasibility of use of more novel high spatial resolution TLDs, including silica beads for lung radiotherapy postal dosimetry audits (Jafari et al., 2017) and Ge-doped optical fibres for high energy photon beam audits (Fadzil et al., 2014; Noor et al., 2014).

In present work, we report on the potential for use of fabricated Ge-doped optical fibres in postal dosimetry audits of high energy electron beams. The optical fibres provide convenient properties such as ease of handling, reusability and cost effectiveness (Bradley et al., 2012), also offering sufficient sensitivity and dose response linearity when subject to electron irradiation (Nurasiah et al., 2020) as well as well-controlled signal fading over time (Noor et al., 2012). In addition, a special characteristic of optical fibres is their high spatial resolution, demonstrated in the studies of radiotherapy dosimetry of small-field radiation (Lam et al., 2020) and *in-vivo* dose verification measurements (Alyahyawi et al., 2021), offering evidential support that the optical fibres can be a good candidate for utilisation in advanced remote dosimetry audits.

Prior dosimetric investigations of these fibres have looked at signal fading, linearity of dose-response, and energy- and dose-rate dependence, finding Ge-doped dosimeters to offer desirable performance, comparable to TLD-100 (Entezam et al., 2016). Using 6% mol Ge-doped optical fibres, optimal in sensitivity and excellent in linearity of dose response within the intended dose range for use in the radiotherapy dosimetry audit (Nurasiah et al., 2020), the work herein now represents the first postal dosimetry audit study of high-energy electron beams, with irradiations covering both reference and non-reference conditions.

2. Materials and methods

2.1. Characterisation of the fibre dosimeters

The optical fibres used in this study were made of pure silica (SiO_2) doped with 6% mol germanium (Ge), 483 μm-diameter for cylindrical fibres (CF) and 85 μm × 270 μm for flat fibres (FF), seeking to accommodate the low penetration capability of electrons relative to photons. All fibres were cut to 6 ± 1 mm long to form individual fibres. Prior to irradiation, any presence in the fibres of residual TL signal was eliminated via annealing (recognising the possibility during fabrication of chemoluminescence defects, strain imposed defects and other such effects), use being made of a furnace (Carbolite, Derbyshire, United Kingdom). The annealing was performed at a maximum temperature of 400°C for 1 hour, followed by slow cooling for 8 hours to room temperature. After annealing, the fibres were loaded into small black polymer capsules, intended to avoid light exposure during periods of storage, pre- and post-irradiation. The particular opaque polyethylene capsules are 3 mm in diameter, 15 mm long, with 1 mm thick walls (Fig. 1). The capsule volume in the absence of the dosimeter (with potential for an air gap) was approximately 0.11 cm^3. This is relatively small compared to the parallel plate ionization chamber PPC 40 (IBA Dosimetry GmbH, Schwarzenbruck, Germany) used in the electron beam dosimetry, with sensitive volume of 0.40 cm^3, considered negligible in polarity and perturbation effects. In addition to the capsules to be irradiated, several sets of control capsules were prepared in order to monitor transit dose that could arise from background radiation and any unintended exposure to irradiation, and to observe unexpected fading during postage. Each capsule has been made to contain 5 to 10 individual fibres, grouped according to sensitivity to within 5%. This experiment was made by irradiating the dosimeters to a known dose of 2 Gy using a 9 MeV electron beam, at 100 cm source to surface distance (SSD), 10 × 10 cm^2 field size, dose delivered at a rate of 400 cGy/min. The dosimeters were placed at the depth or measurement, Z_{ref} using a slab water phantom. The fibre sensitivity was calculated as a mean of readings of the dosimeters after removing outliers, dividing the mean of background corrected readings for each dosimeter. This process was repeated twice to ensure reliability. After irradiation in the UK, the irradiated and control fibres were returned to Malaysia via a courier service for readout using a TLD reader, Harshaw 3500 (Thermoelectron Corporation, USA), the particular device being located at the Malaysian Nuclear Agency, also the home of the SSDL. The temperature correction factor due to temperature variation between the UK and Malaysia was negligible as the fibres were found to be temperature independent from 5 °C up to 50 °C (Noor et al., 2014). The time-temperature profile (TTP) and the glow curve analysis of fabricated fibres in respect to megavoltage electron beam reported by Kandan (2021) was applied to the readout of the CF and FF signals.

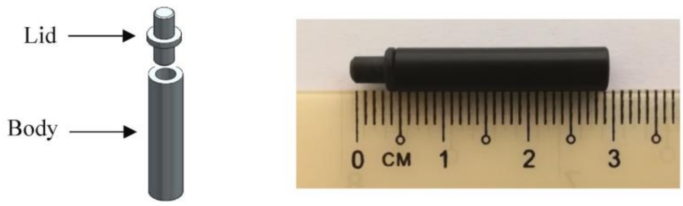

Fig. 1. The polyethylene capsule (a) components and (b) overall dimension measurement (Fadzil et al., 2022).

2.2. Determination of fabricated Ge-doped fibres dosimetric characteristics

The dosimetric characteristics of fabricated Ge-doped optical fibres were investigated for signal fading, linearity dose-response, energy- and dose-rate dependence, the detectors having been subjected to high energy electron beams. These particular irradiations were performed in the UK at the Royal Surrey County Hospital, using an Elekta Synergy® linear accelerator. All irradiations of the fibres were performed under reference conditions, the fibres being placed at a measurement depth, Z_{ref} on the solid water phantom with a 10 cm × 10 cm field size at the phantom surface and a Source-Surface Distance (SSD) of 100 cm (IAEA, 2000).

2.2.1. Signal fading

To study signal fading the fibres were irradiated to an absorbed dose of 2 Gy at a rate of 400 cGy/min, use being made of the same 9 MeV electron beam. The fibres were readout on a regular basis over a period of four-months. Over this period, the capsules were kept at room temperature within a closed cabinet to avoid direct sunlight and ultraviolet radiation that might otherwise contribute to the development of background signal. Study over such a protracted period of time accommodates radiotherapy centre audits in which delayed return of irradiated fibres for analysis can occur. Each data was then normalized to the first reading. An exponential function was fitted to the data to determine the fading correction factor, k_{fading}. The error bars (coverage factor, k=1) were calculated from the standard deviation of the TL signals of the total fibre samples.

2.2.2. Linearity of dose-response

To establish the linearity of dose-response the fibres were irradiated to a range of doses from 1 to 3 Gy, to cover the dose of 2 Gy which is used conventionally in radiotherapy dosimetry remote audits. The dose was delivered in 0.5 Gy increments, a dose rate of 400 cGy/min being applied for 6- and 12 MeV electron beams. The net TL signals were corrected with k_{fading} to obtain actual TL signals. A linear function between TL signals and absorbed dose delivered to fibres was plotted to ascertain a dose-response correction factor, $k_{linearity}$. The trend in linearity of response was compared to that obtained in previous studies.

2.2.3. Energy dependence

The fibres were exposed to a range of nominal energies as typically utilised in radiotherapy, namely 6, 9, 12, 16, and 20 MeV, with delivery of 2 Gy absorbed dose at a dose rate of 400 cGy/min. The net TL signals, corrected with k_{fading}, were obtained. Each set of data was normalized to the 6 MeV electron beam energy and the correction factor, k_{energy} for each energy was determined. The beam energy dependence was further assessed using a one-way between group analysis of variance (ANOVA), a parametric statistical test to evaluate the significant difference of mean TL signal with different electron energies using IBM SPSS Statistics Version 27.

2.2.4. Dose rate dependence

In evaluating the dose-rate dependence, the fibres were irradiated at dose rates of 100, 200, 300, and 400 cGy/min, delivering 2 Gy absorbed dose using 6 MeV and 12 MeV electron beams. The actual TL signal was found from the net TL signals corrected with k_{fading}. Each set of data was normalized to the dose-rate of 400 cGy/min, the latter being a commonly used dose-rate in clinical radiotherapy. The fibre dose-rate correction factor, $k_{doserate}$ was identified. The one-way ANOVA statistical test was run to test the statistically significant difference of mean TL signal and dose-rate.

2.3. Preliminary Electron beam therapy audit using Ge-doped optical fibres

The practicability of using fabricated Ge-doped optical fibres as a transfer detector was further checked in a preliminary audit of a high energy electron beam, carried out under reference and non-reference conditions and performed at a radiotherapy centre in Malaysia. Three capsules containing some 8 to 10 cylindrical and flat fibres were prepared for the audit, two to be irradiated using a 6 MeV electron beam, and the other to serve as a control. For the reference condition, the capsule was irradiated with 2 Gy absorbed dose at measurement depth, Z_{ref} in water at the beam central axis with 10 cm × 10 cm field size at the water phantom surface and SSD of 100 cm. For the non-reference condition, the capsule was irradiated at a dose of 2 Gy in water at the beam central axis with a field size of 6 cm × 6 cm, at depth of maximum dose, Z_{max} and 100 cm SSD.

The measured absorbed dose, $D_{measured}$ was calculated from the fibre readings using equation (1), as follows:

$$D_{measured} = M \times N_{fibre} \times k_{fading} \times k_{linearity} \times k_{energy} \times k_{doserate} \tag{1}$$

where M is the mean TL yield per unit mass (nC/g), N_{fibre} is the calibration coefficient of the optical fibres (Gy/nC/g), k_{fading} is the fading correction factor, $k_{linearity}$ is the dose-response correction factor, k_{energy} is the energy correction factor and $k_{doserate}$ is the dose- rate correction factor.

The results of the audit were expressed as the percentage deviation between the measured dose, $D_{measured}$ using the fibres and the stated dose, D_{stated} as obtained from electron beam calibration. To be in accord with the International Commission on Radiation Units and Measurements (ICRU) Report 24 recommendation of a limit on tolerance (5% at the 95% confidence level) (ICRU, 1976), results should comply within that acceptance limit.

2.4 Estimation of measurement uncertainty

The combined standard uncertainty was evaluated from the combined effect of random (Type A) and systematic uncertainties (Type B) following the "Guide to the expression of uncertainty in measurement" (JCGM, 2008). The overall combined standard uncertainty addresses individual components related to the determination of the measured dose from the optical fibres; this includes dosimeter reading, calibration coefficient, fading correction factor, dose response correction factor, energy correction factor and dose rate correction factor.

3. Results and Discussion

3.1. Dosimetric characteristics of fabricated Ge-doped optical fibre

3.1.1. Signal fading over time

A total of 8 capsules containing CF and FF were irradiated to an absorbed dose of 2 Gy using a 9 MeV electron beam, another 8 capsules being kept as control for background radiation monitoring. One capsule of control fibres was read out on the same day as the irradiated fibres. The change in TL signal was observed from the 15th day post-irradiation through to 120 days after irradiation. All TL signals for CF and FF were normalized to the TL signal obtained at day fifteen post-irradiation as shown in **Fig. *2***. The normalization point was set at day fifteen after irradiation since that is a typical period of delay in having radiotherapy centres return irradiated dosimeters to the laboratory. Moreover, this time delay is needed to allow stabilisation of TL signal within the optical fibres due to the existence of more rapid fading during the first 10 days post irradiation (Noor et al., 2016). The graph shows that there is fading loss of TL signals from day 15 post-irradiation to day 120, amounting to 26% and 20% loss within these periods for CF and FF, respectively. These findings are consistent with recent studies by Nurasiah et al. (2020), reporting a TL signal loss for CF and FF of 29.7% and 26.9%, respectively. To determine the actual TL signal following a certain time frame, the readout TL signal needs to be corrected with a fading correction factor, k_{fading} as previously described.

3.1.2. Linearity of dose response

The fibres were evaluated for linearity, response being checked using different absorbed doses from 1- to 3 Gy, with electron beam energies of 6- and 12 MeV. From **Fig. *3***, the results show the FF fibres to provide superior TL yield per unit mass, more than 50% compared to the CF. This may be explained in terms of existence of more electron-hole traps as the FF have larger surface area than that of the CF (Nurasiah et al., 2020). Both fabricated fibres demonstrate linear response, with least determination coefficients R^2 close to 1 for all cases (eg R^2 of 0.98 for CF at 6 MeV), the TL yield per unit mass acquired from the fibres and the absorbed dose determined from the ionization chamber accordingly being strongly correlated. Even though the y-intercepts were not found to pass through the origin, the values did not contribute significantly in measured dose determination. The dose-response correction, $k_{linearity}$, derived from the linear equations, is used in obtaining the measured dose. Overall, the results are consistent with previous research for electron irradiations (Zakaria et al., 2020).

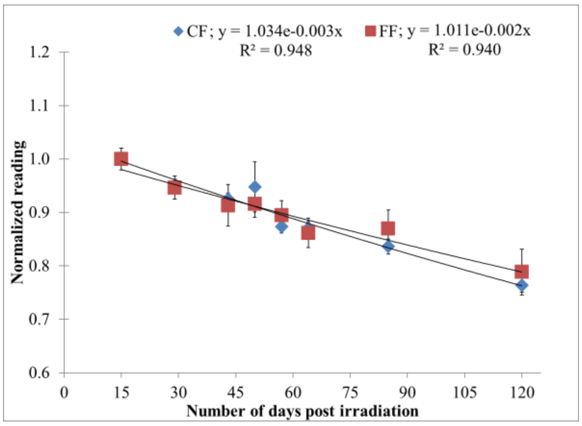

Fig. 2. TL signal fading for CF and FF, from 15th and 120th day post-irradiation. The lines are plotted with an exponential function and serve as a guide to the eye.

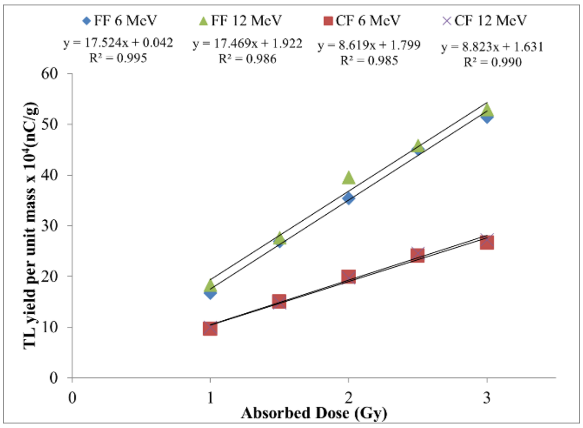

Fig. 3. Linearity of response of CF and FF for doses between 1.0- and 3.0 Gy for 6- and 12 MeV electron beams. In respect of TL yield per unit mass, the error bar for each point was found to be less than the size of the data points.

3.1.3. Beam-energy dependence

The results of electron beam energy dependency for energies 6- up to 20 MeV are presented in **Fig. *4***. The TL yields for each energy were normalised to that at 6 MeV, the latter being commonly used in radiotherapy. Energy corrections from 6- to 20 MeV range from 1.052 to 1.067 and 0.915 to 1.119 for the CF and FF respectively. The one-way ANOVA statistical test was used to determine whether a difference in mean TL yield exists with beam energy. Inspection of Shapiro-Wilk, normal Q-Q plot and box plot statistics indicated that the assumption of normality was supported for each of the three conditions. Levene's statistic was non-significant and thus the assumption of homogeneity of variance was not violated. The results show the greatest mean rank of TL yield for CF was at 9- and 15 MeV (Mean rank = 3.67) while the least was at 6 MeV (Mean rank = 1.33). The ANOVA test for CF indicated the mean rank of TL yield to vary significantly across the five electron beam energies investigated, with $F(4,43) = 4.843$, $p = .003$, $\eta^2 = 0.311$. For FF, the greatest mean rank of the TL yield was at 12 MeV (Mean rank = 4.80), the least being at 9 MeV (Mean rank = 1.60), with $F(4,33) = 6.657$, $p = .001$, $\eta^2 = 0.477$. The p-value of less than .05 indicated there to be statistically significant differences between the mean rank of TL yield and electron beam energy for both fibres. Accordingly, users need to apply an energy factor, k_{energy} in obtaining the corrected measured dose.

3.1.4. Dose-rate dependence

Fig. *5* shows the results of dose-rate dependence for irradiations from 100 to 400 cGy/min using 6- and 12 MeV electron beams, TL yields being normalized to that obtained at 400 cGy/min. For CF the rate corrections for 6- and 12 MeV electron beams range from 0.975 to 0.994 and 0.924 to 0.965 respectively while for FF the corresponding corrections ranged from 1.029 to 1.070 and 1.023 to 1.087. The ANOVA assumptions of normality and homogeneity of variance were not violated, and the Levene's statistic was not significant. The greatest mean rank of the TL yield for CF at 6 MeV was found to be at 100 cGy/min (Mean rank = 3.20) and the least at 400 cGy/min (Mean rank = 2.00), with $F(3,30) = 0.526$, $p = .668$, $\eta^2 = 0.050$. At 12 MeV, the greatest mean rank for CF was at 200 cGy/min (Mean rank = 2.89) and the least was at 100 cGy/min (Mean rank = 1.67) with $F(3,35) = 6.706$, $p = .001$, $\eta^2 = 0.365$. For FF, the results demonstrate the greatest mean rank of the TL yield at 6 MeV to be at 300 cGy/min (Mean rank = 3.00) while the least was at 400 cGy/min (Mean rank = 1.83) with $F(3,28) = 2.411$, $p = .088$, $\eta^2 = 0.205$. At 12 MeV, the greatest mean rank of TL yield for FF was at 300 cGy/min (Mean rank = 3.17), the least being at 400 cGy/min (Mean rank = 1.83), with $F(3,28) = 1.987$, $p = .139$, $\eta^2 = 0.176$. Accordingly, no statistically significant variation was found in mean rank of TL yield and dose-rate for both fibres, as indicated by the p-value of greater than .05.

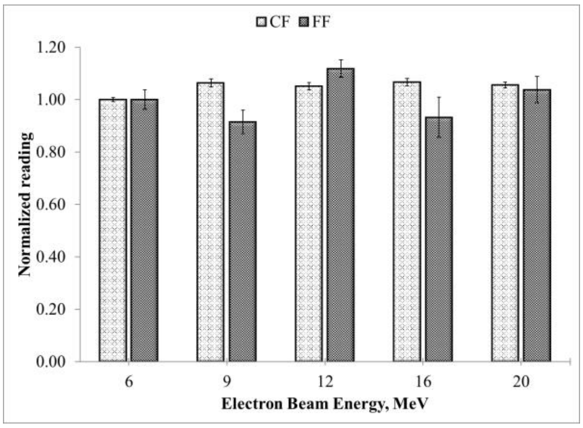

Fig. 4. Energy dependence of CF and FF for electron beam energies 6- to 20 MeV.

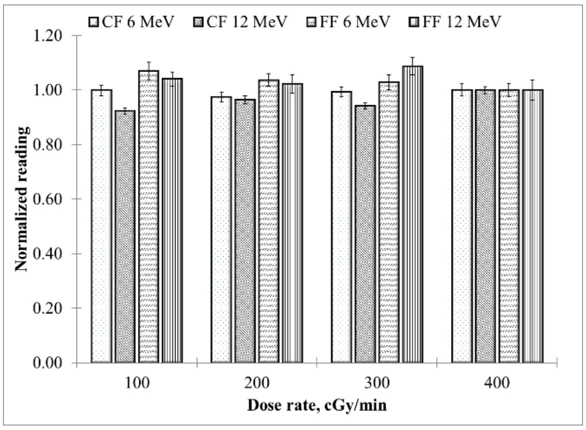

Fig. 5. Dependence of CF and FF for dose-rates 100- to 400 cGy/min using 6- and 12 MeV electron beams.

3.2. Trial audit for high energy electron beam under reference and non-reference conditions

Results of the trial audit for electron beam therapy under reference and non-condition using a 6 MeV electron beam are presented in Table 1. The percentage deviation of mean measured dose for CF and FF from stated dose are shown to be within ± 5%, negative percentage deviation indicating user dose estimates greater than the stated dose. The mean of the distribution of percentage deviations was - 0.15% and the standard deviation was 3.43%. These results are well within the tolerance of ± 5% recorded in ICRU Report No. 24, no further action being indicated for the particular centre audited in the trial. In contrast, centres with results outside the acceptance limit would trigger a need for further investigation in order to identify the causes of deviation; follow-up irradiation would need to be performed without delay to mitigate the likelihood of radiation accidents and errors during radiotherapy.

Table 1. The audit trial of electron beam therapy for reference and non-reference conditions.

Condition	Fibre	Stated dose, D_{stated} (Gy)	Mean measured dose, $D_{measured}$ (Gy)	% Deviation relative to stated dose	$\frac{\text{Mean dose}}{\text{Stated dose}}$
Reference	CF	2.00	2.06	-3.09	1.03
	FF	2.00	1.98	1.16	0.99
Non-reference	CF	2.00	2.06	-2.76	1.03
	FF	2.00	1.92	4.11	0.96

3.3 Uncertainty analysis

The combined standard uncertainty for determination of measured dose from the optical fibres are summarized in Table 2. The largest uncertainty in this study was found to arise from the uncertainty of the dose response correction factor, at 4.95% and 7.26% for CF and FF respectively. The dose rate correction factor contributed to the least uncertainty at 0.19% and 0.01% for CF and FF respectively. The quadratic summation of all components leads to an overall combined uncertainty of 5.99% for CF and 8.20% for FF under the reference condition and 5.91% for CF and 7.96% for FF under non-reference conditions.

Table 2. Estimated relative standard uncertainty of measured dose from optical fibre.

Uncertainty component	Relative standard uncertainty (%)			
	Reference condition		Non-reference condition	
	CF	FF	CF	FF
Dosimeter reading, *M*	1.57	2.41	1.34	1.40
Calibration of the dosimetry system, *N*	1.45	1.44	1.45	1.44
Fading correction factor	0.23	0.12	0.23	0.12
Dose-response correction factor	4.95	7.26	4.95	7.26
Energy correction factor	2.55	2.58	2.55	2.58
Dose- rate correction factor	0.19	0.01	0.19	0.01
Combined uncertainty	5.99	8.20	5.91	7.96

4. Conclusions

This work gives a direct comparison of two types of fabricated Ge-doped optical fibres in terms of their basic dosimetric characteristics for use in postal audits of high energy electron beams applied in radiotherapy. The current findings demonstrate the feasibility of use of either of the two types of fibres as an alternative detector to TLD-100 for postal audit purposes. Indeed, within the present data sets there appears to be no indication that would identify there being a greater advantage or disadvantage in application of either of the two types, with no trend apparent. However, further investigations of the determination of appropriate correction factors to be applied in the absorbed dose measurements for fibres are needed. The audit result of electron beam therapy in reference and non-reference conditions using CF and FF reveals conformity to the acceptance limit of ±5%. To strengthen the application of radiotherapy audits in Malaysia, it would seem that efforts towards electron beam audits can be extended in building upon this initial trial and will become a necessity in future work.

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