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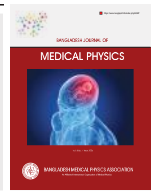

Evaluation of a Miniature Ge-Doped Silica Optical Fiber Radioluminescence Dosimeter for Absolute Dose Measurement in a 6 MeV Electron Radiotherapy Beam

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ABSTRACT

In radiotherapy, absolute dosimetry has traditionally relied on ionization chambers, which provide high accuracy but are relatively bulky and expensive. But in contrast, miniaturized radioluminescence (RL) detectors present a promising alternative, offering compact size, real-time readout, and reduced cost. This study aims to evaluate the dosimetric performance of a Ge-doped silica optical fiber ((SiO_2:Ge), with dimensions of 1 mm in diameter and 1 mm in length, as a radioluminescence (RL) detector for absolute dose measurements in a 6 MeV electron beam generated by a Varian Clinac-iX linear accelerator. A SiO2:Ge was coupled to a 1 mm silica optical fiber and positioned at a depth of 2.4 cm in a water-equivalent bolus, corresponding to the R_{50} for 6 MeV electrons, with a source-to-surface distance (SSD) of 100 cm. Irradiations were delivered using a Varian Clinac-iX at a dose rate of 400 MU/min under controlled room conditions (20°C, 101320 Pa). The RL signal was transmitted via the optical fiber to a myDoz® RL/OSL dosimetry system, which recorded the emitted photon counts. Calibration was carried out with reference doses of 1 Gy and 5 Gy, and the response was subsequently validated at 2 Gy. With the SiO_2:Ge in place, photon counts of 22340 and 111413 were recorded at 1 Gy and 5 Gy, respectively, while corresponding measurements without the crystal yielded 20017 and 99832 counts. Linear calibration predicted counts of 44608 (with sample) and 39,971 (without sample) for a 2 Gy exposure. The experimentally measured values of 44539 and 39940 differed from the predictions by less than 0.3%, thereby confirming the excellent linearity of the detector response. This 1 mm × 1 mm Ge-doped silica optical fiber RL dosimeter demonstrated a highly accurate and linear dose response in 6 MeV electron beam irradiation. This study reveals that its sensitive volume is smaller than that of conventional ionization chambers, the detector presents a promising, low-cost approach for small-field and in vivo dosimetry.

1. Introduction

Accurate and reliable dosimetry is fundamental to the practice of radiotherapy, ensuring that prescribed radiation doses are delivered to the target volume with both clinical efficacy and patient safety. Precision in dose measurement directly impacts treatment outcomes by maximizing tumor control while minimizing exposure to surrounding normal tissues [1]. Usually, ionization chambers have been regarded as the gold standard for reference dosimetry. Their widespread use stems from their well-characterized response, long-term stability, and traceability to national and international standards. Nevertheless, the relatively large sensitive volumes of ionization chambers, typically in the range of 0.1 to 0.6 cm^3, corresponding to diameters of several millimeters, impose limitations in certain clinical contexts. In particular, their spatial averaging effects and physical size hinder their suitability for small-field dosimetry (e.g., stereotactic radiosurgery, intensity-modulated radiotherapy) and for in vivo applications, where high spatial resolution and minimal field perturbation are essential [2].

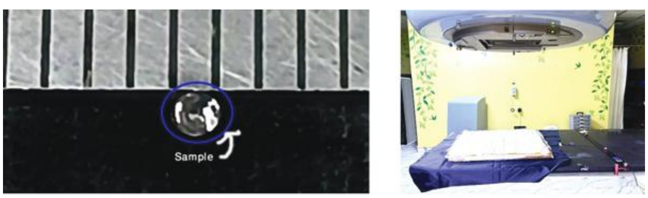
To overcome these challenges, the researchers are trying to adopt alternative dosimetry techniques worldwide. Among these, radioluminescence (RL) dosimetry has emerged as a promising option. In RL systems, absorbed radiation energy is converted into optical photons, which can be detected and quantified in real time. This principle offers several advantages: the potential for continuous dose monitoring, the feasibility of miniaturization, and a reduced impact on the radiation field compared with conventional detectors [3]. Semiconductor-based RL dosimeters, in particular, have demonstrated significant promise owing to their high density, sensitivity, and compact form factor. Within this category, Ge-doped silica optical fibre (SiO_2:Ge) has attracted increasing attention. The incorporation of Ge atoms introduces defect centers within the silicon lattice, thereby enhancing luminescence efficiency relative to pure silicon. This property makes SiO_2:Ge an attractive material for the development of highly sensitive and miniaturized RL detectors [4,5].

The present study investigates a miniature SiO_2:Ge detector with dimensions of 1 mm in diameter and 1 mm in length, i.e, active volume of 0.0008 cm^3, coupled to an optical fiber for photon transport and connected to a myDoz® RL/OSL dosimetry system for signal readout. The detector was evaluated under clinical irradiation conditions using a Varian Clinac-iX linear accelerator delivering 6 MeV electrons. The work highlights the detector's extremely small size compared with conventional ionization chambers, emphasizing its potential for application in small-field dosimetry and real-time in vivo measurements [6, 7].

2. Materials and Methods

2.1. Probe Preparation

The dosimeter system employed in this study consists of a Ge-doped silica optical fiber (SiO_2:Ge) serving as the active material. This sample has dimensions of 1 mm in diameter and 1 mm in length, an active volume of 0.0008 cm^3, enabling a highly compact detector volume suitable for small-field dosimetry applications.



(a) (b)

Fig. 1: Graphical representation of (a) 1mm length and 1 mm diameter Ge-doped silica optical fibre (SiO_2:Ge), (b) sample positioning under bolus.

2.2. Dosimetry System

To efficiently guide the emitted RL photons, the sample is optically coupled to a 1 mm silica optical fiber using optical grease, which minimizes reflection losses and ensures effective light transmission. The guided photons are subsequently delivered to a myDoz® RL/OSL dosimetry system, which serves as the readout device. It provides highly sensitive photon counting, thereby enabling accurate detection and quantification of the luminescence signal generated during irradiation.

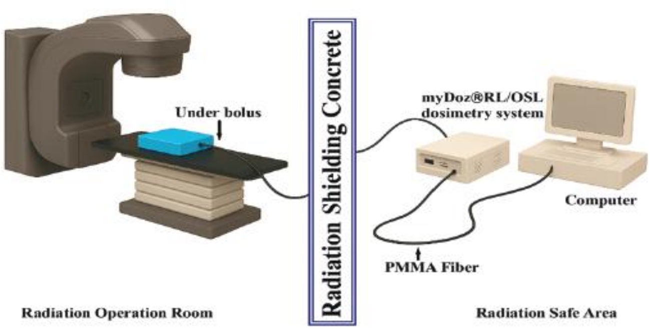


Fig. 2: Schematic diagram of experimental setup.

2.3. Irradiation Setup

The measurements were performed using a Varian Clinac-iX medical linear accelerator, which delivers a 6 MeV electron beam. The setup employed a source-to-surface distance (SSD) of 100 cm, with the detector positioned at a depth of 2.4 cm in water-equivalent bolus, corresponding to the R_{50} depth for 6 MeV electrons. The irradiation was performed at a dose rate of 400 MU/min, under controlled environmental conditions of approximately 20°C temperature and 101320 Pa pressure. The RL counts were recorded for irradiations of 1 Gy and 5 Gy, both with and without the Ge-doped silica optical fiber in place. To verify calibration accuracy, an additional measurement was performed at a dose of 2 Gy. For reference dosimetry, a calibrated parallel-plate ionization chamber was used, following the guidelines of IAEA TRS-398. The recorded RL data were analyzed by performing linear fits of counts versus dose for both the "with sample" and "without sample" conditions. From these fits, the sensitivity values (counts per Gy) and corresponding intercepts were determined. To assess calibration accuracy, the measured counts at 2 Gy were then compared with the predicted values obtained from the calibration curves.

3. Results

3.1 Data Calibration

Radioluminescence (RL) counts were obtained for irradiations at doses of 1 Gy and 5 Gy, both in the presence and absence of the Ge-doped silica optical fiber. To further assess the accuracy of the calibration, an additional verification measurement was conducted at a dose level of 2 Gy, with the corresponding results presented in the calibration Table1.

Table 1: Calibration Data Table

Dose (Gy)	Counts With Sample (Measured)	Counts Without Sample (Measured)	Counts With Sample (Predicted)	Counts Without Sample (Predicted)
1	22340	20017	22340	20017
2	44539	39940	44608	39971
5	111413	99832	111413	99832

From these data, calibration curves were subsequently constructed.

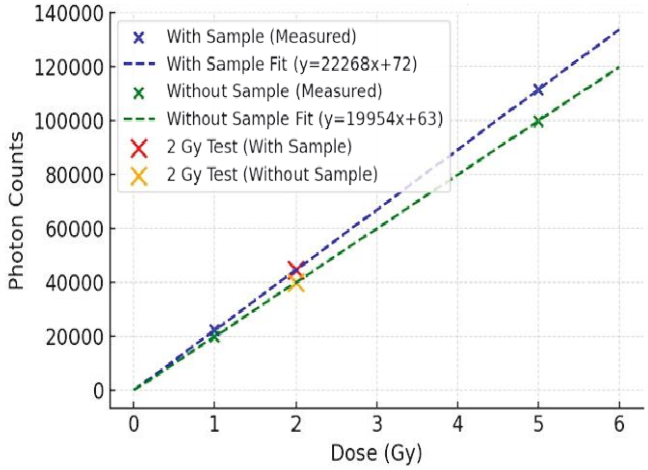


Fig. 3: Calibration graph for with and without sample.

The calibration analysis revealed distinct fitting parameters under the two conditions. When measured with the sample, the calibration yielded a sensitivity of approximately 22768 counts per Gy, accompanied by an intercept of -428. In contrast, the calibration performed without the sample produced a sensitivity of approximately 19954 counts per Gy, with an intercept of +63. These results underscore the influence of the sample on the calibration response and highlight the consistency of the measurement approach.

3.2 Data Analysis

The RL response exhibited strong linearity across the dose range of 1 to 5 Gy, with a coefficien t of determination (R_2) exceeding 0.99. Furthermore, the validation measurement at 2 Gy demonstrated exceptional accuracy, showing agreement within 0.3% of the predicted value in both cases. These findings highlight the method's excellent reproducibility and confirm its reliability for precise dosimetric assessment.

4. Discussion

This study confirms the feasibility of using a 1 mm × 1 mm Ge-doped silica optical fiber as an RL dosimeter. Despite its miniature sensitive volume, the detector produced a strong, stable signal with high linearity. The ability to achieve absolute dose accuracy comparable to ionization chambers highlights the promise of miniature semiconductor RL dosimeters. The small size enables applications in:

- Small-field dosimetry (stereotactic radiotherapy, IMRT)
- In vivo patient monitoring
- Areas where ion chambers are impractical

Compared to the bulky volumes of ionization chambers, the present detector perturbs the radiation field minimally while maintaining accuracy. Future work should explore energy dependence across multiple beam qualities, long-term stability, and integration into multi-fiber probe arrays.

5. Conclusions

A miniature Ge-doped silica optical fiber RL dosimeter with dimensions of only 1 mm × 1 mm was evaluated in a 6 MeV electron beam delivered by a Varian Clinac-iX under standard clinical conditions. The detector exhibited a clear linear dose response in the range of 1 to 5 Gy, with excellent reproducibility of the measured signals. Validation at 2 Gy showed agreement within 0.3% between measured and predicted values, confirming the reliability of the calibration. Due to its extremely compact size, significantly smaller than conventional ionization chambers, the dosimeter demonstrates strong potential for applications requiring high spatial resolution and minimal perturbation of the radiation field. This work highlights the strong potential of semiconductor-based RL dosimeters in modern radiotherapy dosimetry. Their high spatial resolution, miniature dimensions, and excellent reproducibility make them particularly well suited for advanced clinical applications, including in vivo dosimetry. Moreover, compared with conventional ionization chambers, these detectors offer a cost-effective solution while maintaining accuracy and reliability, thereby opening opportunities for widespread use in both clinical quality assurance and research settings.

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