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Characterisations of a fibre optic dosimetry system for source tracking during HDR Brachytherapy

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Abstract

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Characterisations of a fibre optic dosimetry system for source tracking during HDR Brachytherapy

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Abstract. Brachytherapy is a complex treatment procedure where radioactive sources are inserted in or close to the tumours to destroy the cancerous cells. Due to the unique properties of scintillation plastic detectors, this study was aimed to characterise an innovative fibre optic dosimetry system as a quality assurance tool during HDR Brachytherapy. Scintillating plastic fibres with different scintillation lengths were prepared and then optically coupled to non-scintillating fibres for light transmission. A transimpedance photodiode amplifier was used to detect positional sensitivities of different fibre probes placed within a solid-water phantom at varying distances above an 192-Ir brachytherapy source located within the catheter. Monte Carlo simulation has validated the expected response of the scintillating plastic fibres for multiple dwell positions with demonstrating the variance of detector response with source location. It showed the ability of shorter scintillating fibre lengths to distinguish between varying source locations when the SNR maintained high. However, fully scintillating plastic fibre showed flat response for most dwell positions. The proposed system proved to be appropriate for further clinical investigations, such as simultaneous dose measurement, and providing 3D position reconstruction through in-vivo source tracking.

1. Introduction

Brachytherapy is a complex radiotherapy technique where radioactive sources, with a high dose rate usually 12Gy/h and more, are inserted close to or within the tumour volume to treat cancerous cells. Hence, quality assurance (QA) programs have been established worldwide by introducing sophisticated QA devices for assuring the safe delivery of radiation dose to patients, verifying and tracking HDR source during Brachytherapy treatment to prevent unexpected errors that might lead to disastrous accidents in clinical scenarios [1-4]. Due to the desired properties, such as water equivalence, high spatial resolution, and dose rate independence, that fibre optic scintillation detectors possess compared to other conventional QA tools, they have shown the capability for effectively performing *in-vivo* dosimetry [5]. However, the only disadvantage of such technology is being nearly temperature dependant [6], and also the production of Cherenkov light when charged particles travel at a speed higher than the speed of light in that medium [7], which is considered to be a major source of unwanted signals that need to be corrected for when measuring the dose.

There has been a considerable amount of research on fibre optic dosimetry (FOD) as real-time quality assurance tools in radiotherapy. The continuing growth and the unique properties have undoubtedly attracted the attention of researchers which resulted in a significant number of papers published. At the end of the last century, in 1992, Beddar *et al* introduced the first scintillation fibre optic dosimetry system that resulted in the creation of a scientific revolution in the path of radiation detection and measurements which opened up wide horizons for those who are interested in FOD [8, 9]. However, several research groups around the world have applied this fabulous technology for *in-vivo* dosimetry with so many different radiation modalities. It is worth mentioning the successful implementation of FOD with photon [9-12], electron [13, 14], proton beams [15, 16], radiology [17, 18], and Brachytherapy [19-21]. This study aims to introduce an innovative, portable, cost effective fibre optic system as a QA tool, developed to measure the dose and localise the HDR Brachytherapy source based on the response of multiple fibres in catheters within the treatment volume. In addition, it also aimed to characterise the system in terms of the optical properties and selecting optimal fibre lengths and distance to the Ir-192 source.

2. Materials and Methods

2.1 Preparation of fibre optic probes

Scintillating plastic fibres (BCF-60, Saint-Gobain Crystals USA) with different scintillation lengths (from 10cm to 0.5cm) were in house-prepared and tested before being used. All fibres were finely cut using a sharp cutter, polished using polishing films of different thickness, paint coated, and then optically coupled to a 1m long clear plastic fibres (BCF-98, Saint-Gobain Crystals USA).

2.2 Experimental work

A Monte Carlo simulation was performed using the Geant4 toolkit (4.9.2) to validate the methodology behind converting signal response to source location. A sensitive trans-impedance photodiode amplifier was in-house developed, enclosed in an aluminium shielded box to maintain protection from external interfering sources, connected to data logger through a coaxial cable out to the control room. A solid-water phantom, with a catheter inserted the whole way through, was CT scanned, and dwell positions were digitised using the treatment planning system (TPS). The fibres were placed within a solid-water phantom at varying distances above a 192-Ir brachytherapy source located within the catheter, with dwell positions varied every 2.5 mm.

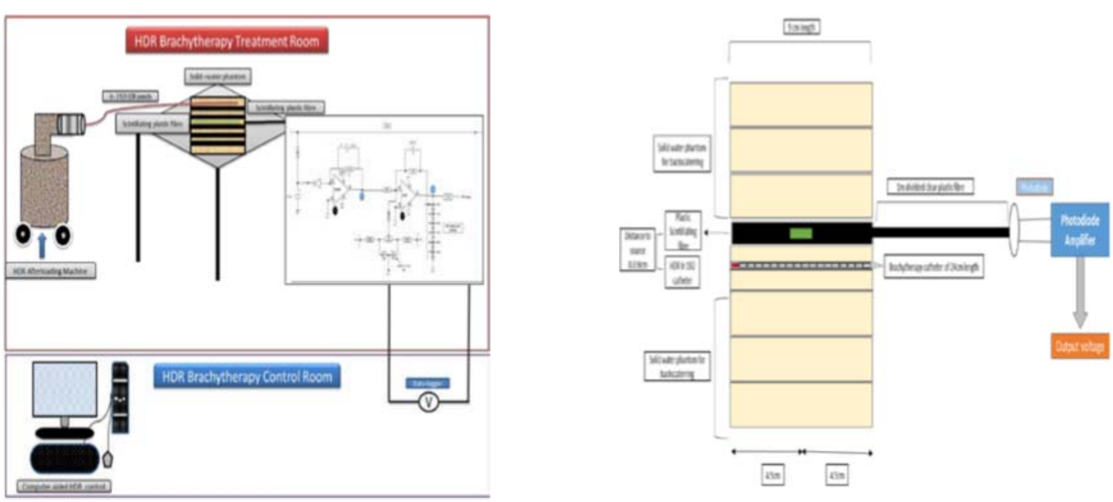

Figure 1. Schematic diagrams illustrate the overall experimental set-up with the electrical circuit designed to conduct the experiment (left), the experimental set-up required inside the HDR Brachytherapy treatment (right).

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3. Results and discussion

3.1 Optical properties of the optical fibre used:

The following table, shown below, shows the main properties of the fibre probes used in this study as stated by the manufacturer (Saint-Gobain Crystals, USA). **A** denotes the clear fibre probe with no scintillating fibre attached, **B** denotes 1 m length of fully scintillating fibre, and **C** indicates the composite fibre that has 7.5 cm scintillating plastic fibre attached to 1 m clear fibre.

Table 1. Properties of the optical fibres probes.

	Fibre probe	Emission colour & Peak (nm)	Scintillation fibre attached	Length of clear fibre	Core Ref Index	Cladding Ref Index
A	Clear fibre (BCF-98)	Clear waveguide N/A	0	1 m	Polystyrene	Acrylic
B	Fully scintillating fibre (BCF-60)	Green (530nm)	1 m	0	n1= 1.60	n2=1.49
C	Partially scintillating fibre (BCF-60)	Green (530nm)	7.5 cm	92 cm		

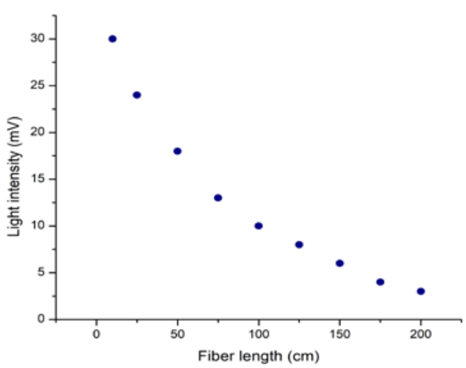

Figure 2. Attenuation of fully scintillating plastic fibre of 2 m long upon interaction with HDR 192-Ir.

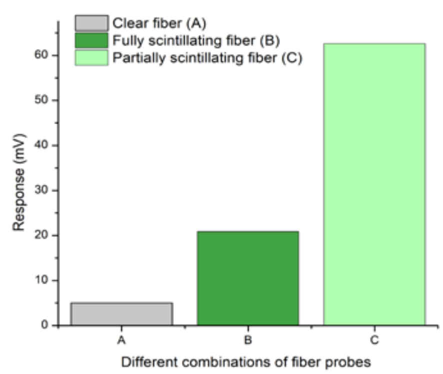

Figure 3. Comparison of three different plastic fibre probes (A, B, C) of the same length upon irradiation with HDR192-Ir, SDD = 8mm.

It is notable from Figure 1 that the fully BCF-60 green emitter, 2 m long and a diameter of 1 mm, exhibits high attenuation due to the nature of the multi-mode fibre and high probability of scintillation mechanism occurred over the whole length of the fibre probe. Attenuation would be minimal if much smaller length of BCF-60 scintillating element was optically coupled to a plastic optical fibre [22]. Hence, it is observed from Figure 2 and Figure 3 that the partially scintillating fibre (C) shows a higher signal (less attenuation) than the fully scintillating fibre (B) which demonstrates lower signal due to higher attenuation of this sort of fibre. However, the signal generated from the clear fibre (A) only being the lowest among other fibre probes and it is attributed to the effect of Cherenkov light produced at a certain threshold which is obviously above the average energy of the iridium source of 380 keV [23]. It accounts for 37.59% of the main signal for the partially scintillating plastic fibre (C) which shows constant behaviour in most conditions.

3.2 Positional sensitivity of the proposed fibre optic dosimetry system for different HDR dwell positions at different source to detector distance

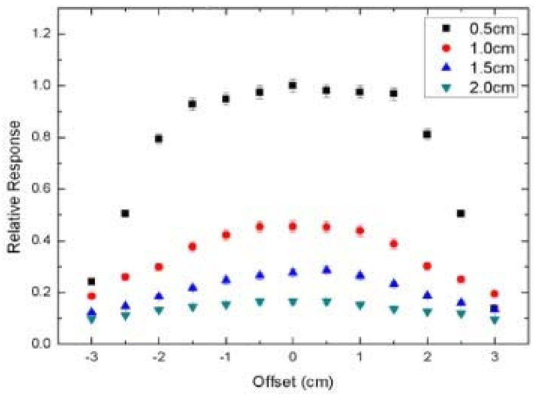

Figure 4. Monto Carlo Simulation derived responses of a 5cm length scintillating fibre with an 192-Ir source at different dwell positions within a catheter, with the catheter to detector distance of 0.5cm, 1cm, 1.5cm and 2cm.

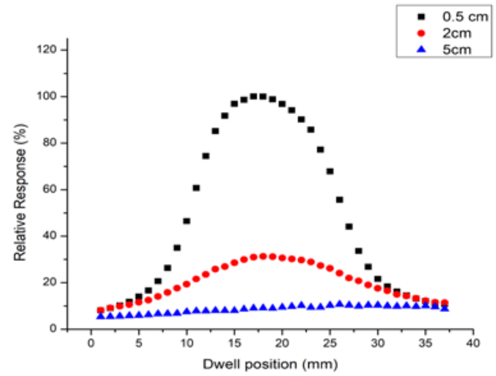

Figure 5. Response of 4cm length scintillating fibre upon irradiated with 192-Ir source at different catheter to detector distances.

The Monte Carlo simulation (Figure 4) demonstrated the variance of detector response with source location, validating the ability of a 3 cm length scintillating fibre and less to distinguish between varying source locations once signal to noise ratio (SNR) maintained high. As can be seen in Figure 5 that the initial investigation has validated the expected response of the scintillating plastic fibres for multiple dwell positions, and high resolution is notably achieved when the detector is placed close to the source (SSD=0.5 cm) and completely invisible when the detector was away from the source (SSD=5 cm)

3.3 The optimal length of scintillating fibre

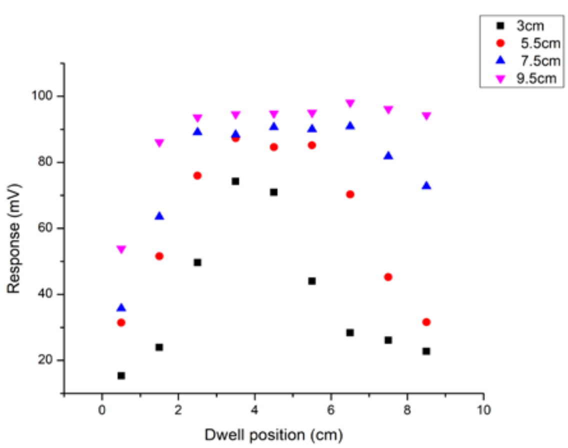

Figure 6. Positional sensitivities of different lengths of scintillating fibres, SDD = 1cm above 192-Iriduim source for multiple dwell positions.

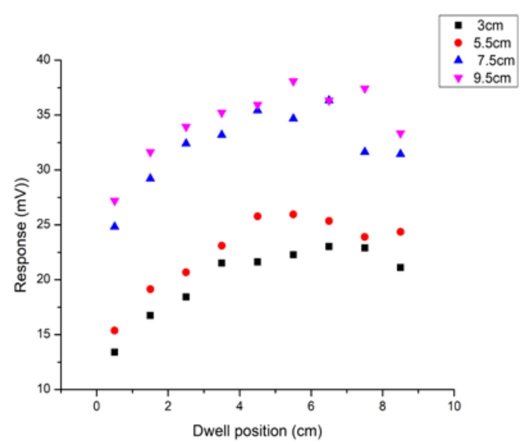

Figure 7. Positional sensitivities of different lengths of scintillating fibres, SDD = 3cm above 192-Iriduim source for multiple dwell positions.

From the above results in both Figure 6 and Figure 7, positional sensitivities were obtained for different fibre lengths and catheter to detector distances. The shorter fibre length, the less signal from the amplifier, which demonstrates poorer signal to noise (S/N) ratio. The 9.5cm of scintillating fibre has a flatted response while HDR source dwelling for a distance from 3cm to 9cm. That would be due to the large sensitive volume of the detector and the contribution of the scintillation signal along with the combination of the Cherenkov and fluorescence signal generated from the optical waveguide (the clear fibre used to transmit the scintillation signal to the photodetector). The 3cm length of scintillating fibre has clearly proven to distinguish between the responses of most adjacent dwell positions when source dwelling every 1 cm. If higher spatial resolution is to be achieved, there is a necessity to reduce the scintillation length but on the account of (S/N) ratio being relatively low. Therefore, (S/N) ratio must be kept high and higher gain must be applied to maintain reasonable signal acquisition. Positional sensitivity for each dwell position was clearly distinguishable upon placing the fibre closely to the source (SSD= 1 cm) and completely unobserved while placing the fibre away from the source (SSD= 3 cm).

4. Conclusion

The proposed fibre optic dosimetry system has been in-house designed and initially investigated. Properties of the optical fibre probes have been demonstrated in terms of attenuation and ideal fibre composition. In addition, response for all possible HDR dwell positions at different distance to the location of HDR source have been theoretically and experimentally demonstrated. The system also was characterised and optimised in terms of selecting optimal fibre length and appropriate SDDs. It proves to be eligible for further clinical investigations, such as simultaneous dose measurement and source localisation. The system has shown its capability for providing 3D position reconstruction through in-vivo source tracking.

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