Dosimetric characterization of an inorganic optical fiber sensor for external beam radiation therapy.

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***Abstract*— The aim of this study was to investigate the dosimetric performance of a novel optical fiber sensor for use in external beam radiation therapy. Repeatability and reproducibility of the output signal, linearity, dose rate and dose per pulse dependence were evaluated. Angular dependence was investigated in the axial and azimuthal planes. The percentage depth dose and lateral dose profiles were measured using the optical fiber sensor system and compared to commercially available detectors such as Exradin W1 plastic scintillator and a PTW-microdiamond detector. The result of this study show that the optical fiber sensor system has good repeatability and reproducibility of the output signal with a maximum deviation of 0.17% and 1.00%, respectively. The system also showed an excellent linearity with dose, and its signal was independent of dose rate. However, the system showed a strong dependence on dose per pulse with 27% deviation from the W1 result at the highest dose per pulse value that was achieved at 75 cm source to surface distance. The system also showed an angular dependence when the incident beam was in the azimuthal plane due to the geometry of the scintillator at the tip of the fiber. The optical fiber sensor over-responded when measuring percentage depth dose curves and lateral dose profiles due in part to the sensitivity of the scintillating material (Gd_2O_2S:Tb) to low energy scattered radiation. However, further investigation is needed to quantify the overall contribution of Cerenkov radiation to the over-response of the optical fiber sensor.**

***Index Terms*— External beam radiation therapy; inorganic optical fiber sensor; radiation dosimetry**

I. INTRODUCTION

The aim of radiotherapy treatment is to destroy tumor tissue while sparing normal tissue as much as possible. Therefore, new radiation therapy treatments techniques such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) use small radiation field sizes and high dose gradients to deliver more conformal doses and tighter margins around tumors. As a result, several international organizations, such as the American Association of Physics in Medicine (AAPM), recommend performing in-vivo measurements during treatment to determine any changes in the planned dose due to uncertainty encountered throughout the many steps of treatment planning and execution [1].

Thermoluminescent dosimeters (TLDs), diodes, metal-oxide semiconductor field effect transistors (MOSFETs), films and electronic portal imaging devices (EPID) have been used for in-vivo dosimetry; however, there are certain inherent limitations [2]. Films and TLDs offer high resolution but are time consuming and are not applicable to real-time dosimetry because they require processing after irradiation. Diodes and MOSFETs are applicable for real-time measurements; however, correction factors which require special care when applied to ensure accuracy from diodes and MOSFETs are energy and temperature dependent with limited life times. Optical fibre sensor (OFS), on the other hand, provide many advantages over these systems for real time dosimetry. One such advantage is the ability to remotely monitor radiation online as a sensor can be positioned several meters from the control electronics. Other advantages are due to the small dimensions of OFS systems, including high spatial resolution and minimally invasive in-vivo applications. OFS systems are also excellent choices for MR-guided radiation therapy systems as they are immune to electromagnetic fields.

An OFS system is comprised of a scintillating material, which can be organic or inorganic, coupled to an optical fibre cable. The scintillation material fluoresces on exposure to ionizing radiation and the resultant emitted fluorescent light penetrates an optical fibre cable and is detected using a photodetector. A drawback that is common to all OFS systems and until recently limited their use in radiation dosimetry is the light generated in the fibre, which is primarily attributed to Cerenkov radiation. Cerenkov radiation is produced when a charged particle travels in a medium at a speed greater than the speed of light. The spectral distribution of Cerenkov light is most intense in the blue and ultraviolet regions of the electromagnetic spectrum. Cerenkov radiation and other light produced in the fibre itself during irradiation are referred to as the stem effect.

Several techniques have been employed to eliminate or minimise the stem effect. Beddar et al. (1992) proposed the background subtraction technique that used two parallel optical

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fibres placed next to each other, one with and one without scintillating materials. The fibre with no scintillating material produces Cerenkov radiation that can be subtracted from the fibre signal with the scintillating materials; however, the spatial resolution can be compromised, and positional uncertainties can produce errors [3]. Spectral discrimination methods are most commonly used to account for Cerenkov radiation. These methods use optical filters to separate the scintillation signal from the Cerenkov signal using the spectral differences between the green (scintillation) and blue (Cerenkov) light being produced [4-6].

Recently, an optical fibre sensor based on inorganic scintillating material terbium doped gadolinium oxysulphide (Gd_2O_2S:Tb) was developed by O`Keeffe et al. [7]. The sensor showed promising characteristics making it a good candidate to use for in vivo dosimetry in radiotherapy and brachytherapy [8-10].

In this work, further characterisation of the Gd_2O_2S:Tb OFS for external beam radiotherapy is presented. The dosimetry properties, including the repeatability of the OFS system response, linearity of the output signal with radiation doses and dose rate and dose per pulse (DPP) dependency of the system, were tested. Percentage depth dose (PDD) and lateral dose profiles were measured for different field sizes and compared to other commercially available detectors.

II. SENSOR DESIGN

The OFS was constructed using a polymethyl methacrylate (PMMA) plastic optical fibre. PMMA optical fibres are generally more robust, flexible, biocompatible and considerably cheaper option when compare to glass optical fibres [11]. The core of the PMMA was micro-machined to make a 700 µm diameter and 7 mm deep cavity (Figure 1). The current design of OFS was achieved through an experimental optimization process [8, 9, 12]. The scintillating material, Gd_2O_2S:Tb, supplied by Phosphor Technologies (UKL65/FR1), was filled into the cavity and sealed with an epoxy. The scintillation material fluoresces on exposure to ionizing radiation, and the resultant emitted fluorescent light penetrates the PMMA optical fibre core and propagates along the fibre to a Hamamatsu multi-pixel photon counting module (MPPC C11208).

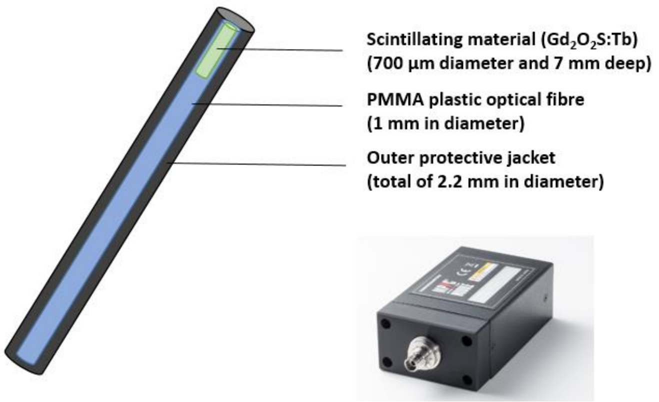

Fig. 1. Schematic representation of the inorganic optical fibre sensor for external beam radiotherapy, showing a 700 µm diameter and 7 mm deep cavity in the core of a PMMA plastic optical fibre and the Hamamatsu multi-pixel photon counting module.

III. MEASUREMENTS

All measurements were carried out with a 6 MV photon beam delivered by an Elekta Versa HDTM linear accelerator (linac) except for PDD and lateral dose profiles, which were performed on an Elekta Synergy operating at a 6 MV photon beam. A solid water phantom was used for all measurements except for PDD and lateral dose profiles, in which a PTW (Physikalisch Technische-Werkstatten, Freiburg, Germany) water tank was used. An insert that mimicked the shape of a Farmer chamber was designed to provide an airtight cavity for the OFS when used in the solid water phantom. The experimental setup, showing the OFS inserted in the solid water phantom using the designed insert is shown in Figure 2.

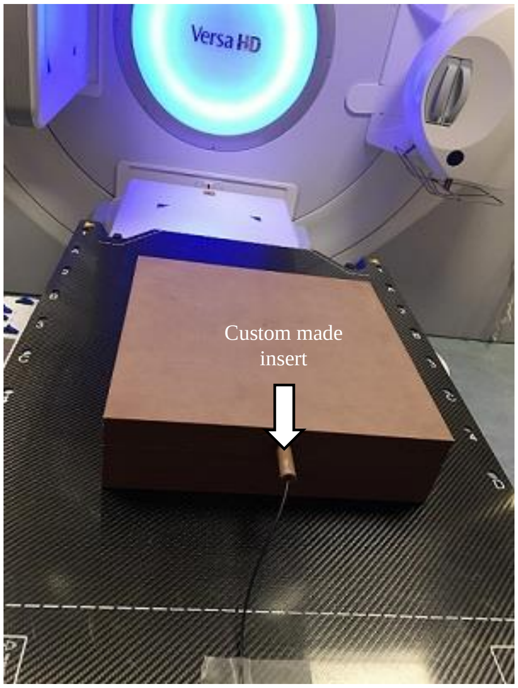

Fig. 2. Experimental setup, showing the custom made insert mimicking the shape of the Farmer chamber to provide an airtight cavity for the OFS inserted in the solid water phantom.

A. *Repeatability and reproducibility*

In order to evaluate the repeatability of the system under high and low dose conditions, the output intensity was measured for 10 successive irradiations using a 6 MV photon beam and two different dose values (100 MU and 20 MU). For each measurement, the dose was delivered using a field size of 10 x 10 cm^2 and dose rate of 600 MU/min. The sensor was placed at a depth of 10 cm in the solid water phantom with a standard source to surface distance (SSD) of 90 cm. Reproducibility was also checked over 5 days by measuring the day-to-day variability of the output signal when irradiating the OFS using the same setup.

B. Linearity of the output signal with dose, dose rate and dose per pulse dependence

The linearity of the output signal of the system with dose was tested by varying the dose delivered to the OFS from 50 MU to 500 MU with dose rates of 600 MU/min using the same exponential setup for evaluation of the repeatability and reproducibility of the system. The variation of the system response with different dose rates was evaluated by increasing the dose rate in steps from 50 MU/min to 600 MU/min.

The DPP dependency of the OFS system was investigated by comparing the response of the OFS to different DPP values with the result from the Exradin W1 plastic scintillator (Standard Imaging Inc., Middleton, WI, USA). The W1 was selected as it was shown to be DPP independent [13].

The different DPP values were obtained by using various SSD settings (75 cm to 130 cm). For each SSD setting, the collimator aperture was scaled to always obtain a 10x10 cm^2 field size at the phantom surface in order to eliminate any effect on the sensor response based on the field size difference. For each measurement, 100 MU was delivered and the detectors were positioned at the same depth (10 cm). Measurements were repeated three times, and the results were normalized to that calculated at 100 SSD.

C. Angular dependence

Variation of the system response with the incident angle of radiation was investigated by positioning the OFS at the linac isocenter inside a 5 cm height and 5 cm diameter home-made cylindrical phantom. A 4x4 cm^2 radiation field size was used and the radiation angle was varied by rotating the gantry at 30^o intervals from 90^o to 270^o in both axial and azimuthal configurations, as shown in Figure 3. Measurements were repeated three times, and the results were normalized to that calculated at 0^o.

D. Percentage depth dose and lateral dose measurements

PDD and lateral dose profiles were acquired in a water phantom at 90 SSD by moving the OFS in a step-by-step mode using the PTW tank controller and delivering 100 MU for each measurement. The results were then compared with PDDs and lateral dose profiles obtained for the same conditions using the commercial Exradin W1 plastic scintillator and a PTW-microdiamond detector.

PDD profiles were acquired for three different field sizes: 10x10 cm^2, 4x4 cm^2 and 2x2 cm^2. The curves were measured at 2 mm intervals in the build-up region and 10 mm up to 30 cm depth in the phantom.

Lateral dose profiles were acquired in the cross-plane direction at a depth of 1.5 cm using a interval size of 2 mm in the penumbra region and 5 mm along the rest of the profile. The uncertainty associated with the reproducibility of the jaws positioning and the positioning accuracy of the water tanks scanning system assumed to be ±1 mm and ±0.1 mm, respectively [14].

IV. RESULTS AND DISCUSSION

A. Repeatability and reproducibility

Figure 4 shows the integrated sum of the optical intensity during the radiation beam for ten consecutive readings using low and high dose values. The system demonstrated very good repeatability with a maximum deviation of only 0.10% and 0.17% from the average value when using 20 MU and 100 MU dose values, respectively. This result was much lower than what was reported for other inorganic scintillator based sensors such as YVO4:Eu^{3+} (0.50%) [15], other detectors based on Optically Stimulated Luminescence (OSL) such as Al_2O_3:C (0.50%) [16] and the commercial W1 plastic scintillator, which was reported by Carrasco et al. (2015) (0.40%) [17]. However it is slightly higher than what was calculated by Beddar et al. (1992) for their organic plastic scintillator detector (0.10%) [18].

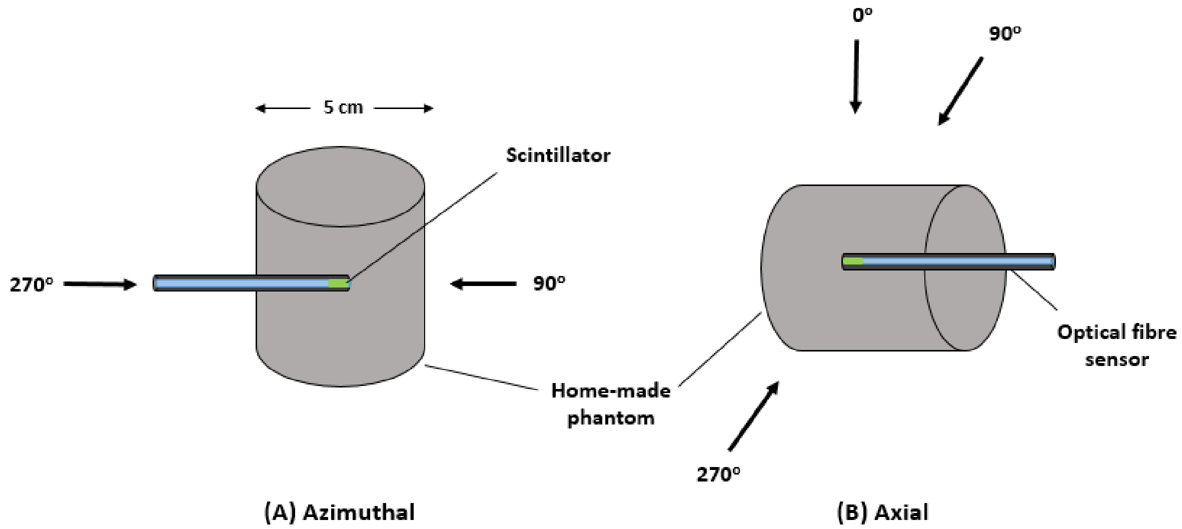

Fig. 3. Schematic representation of the experimental setup employed in the angular dependence investigation. The radiation angle varied from 90^o to 270^o in the (A) azimuthal and (B) axial plane. The 0^o angle in the azimuthal plane is orientated into the page.

The system was observed to have very good reproducibility with only 1.00% day-to-day variation of the output signal when repeated over 5 days, which suggests that the Gd_2O_2S:Tb sensor with its MPPC does not require regular calibration.

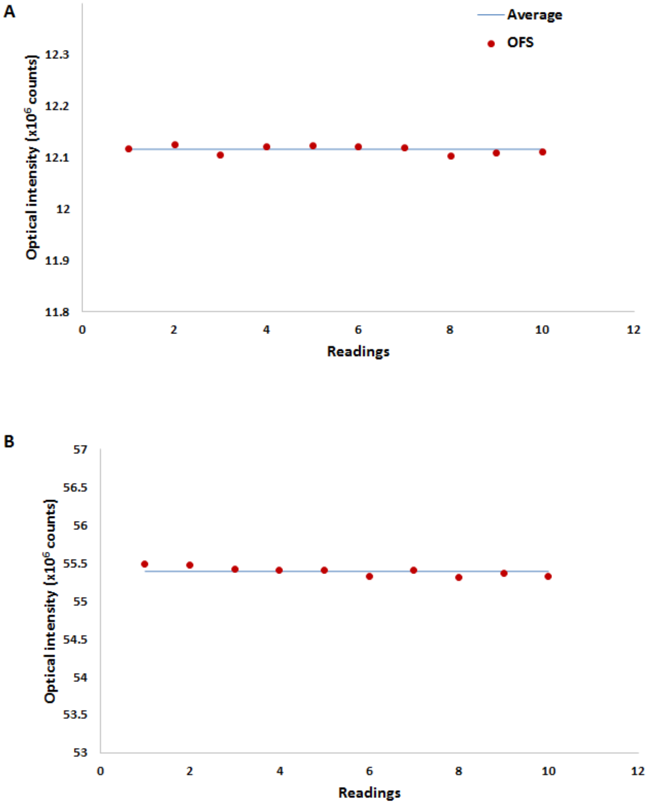

Fig. 4. Repeatability of the output signal of the OFS system for ten successive irradiations, using (A) 20 MU and (B) 100 MU for each measurements.

B. *Linearity of the output signal with dose, dose rate and dose per pulse dependence*

Figure 5 shows the output intensity of the OFS system obtained for different radiation doses. The integrated output signal shows excellent linearity of the OFS system with radiation doses up to 500 cGy with an R^2 of 0.999999.

The response of the sensor was found to be independent of dose rate when varying the dose rate from 50 to 600 MU/min with a maximum deviation of 0.18% from the average value, which was within the repeatability of the system, as seen in figure 6.

The dose per pulse dependence of the system was evaluated by exposing the OFS to different DPP values using different SSD settings (75 cm to 130 cm), and the OFS result was normalized to that calculated at 100 SSD and given as a percentage difference from the W1 scintillator result. As shown in figure 7, the response of the OFS shows a high variation relative to the W1 result in both high and low radiation dose per pulse values. The sensor over-responded to low doses and under-estimate higher dose per pulse values. The maximum deviation was 27 ± 0.68% at the highest dose value (SSD of 70 cm). At low dose values (SSD of 130 cm), the maximum percentage difference was 7 ± 0.14%. This discrepancy suggests a strong dependence of the OFS system on DPP variation.

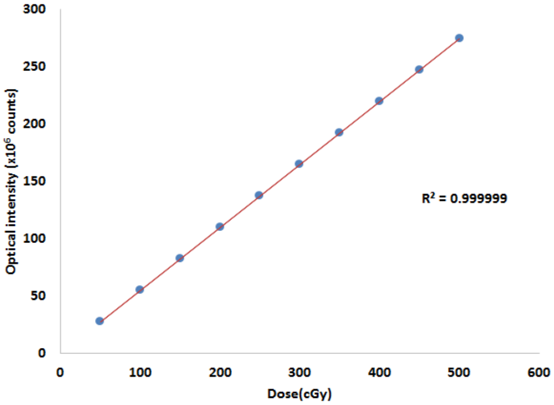

Fig. 5. Linearity of the OFS response to a range of doses from 50 to 500 cGy.

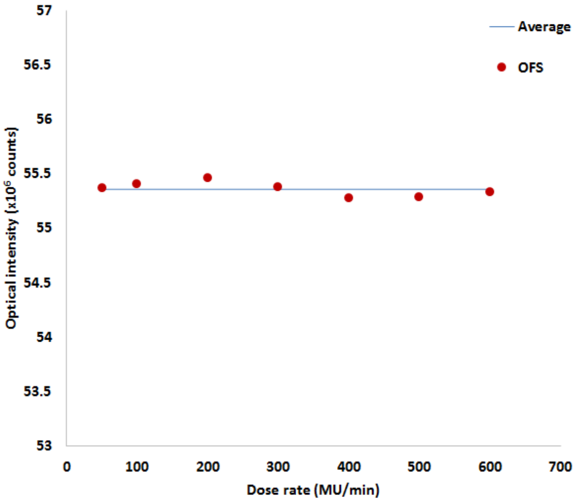

Fig. 6. The OFS response to increase in dose rate from 50 to 600 MU/min.

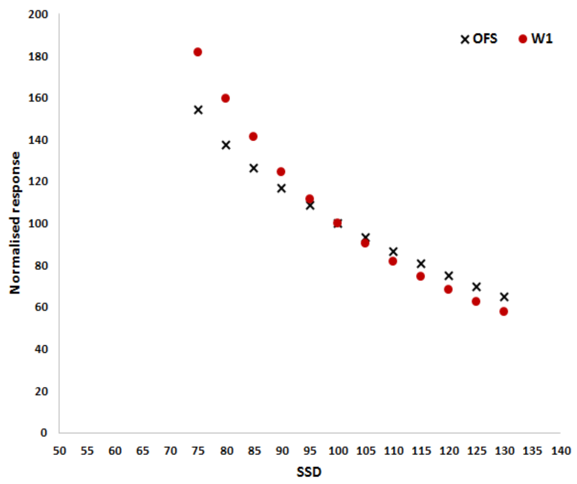

Fig. 7. Dose per pulse dependence for the OFS with respect to the W1 plastic scintillator.

C. *Angular dependence*

The results of the angular dependence of the OFS in the axial and azimuthal planes are shown in figure 8. The sensor responses were normalized to the value acquired at 0°. As the sensor has a cylindrical shape, the sensor response proved to be independent of the incident radiation angle in the axial plane, with a maximum deviation of 0.61 ± 0.13%. In contrast, the sensor showed a strong dependence on the radiation angle in the azimuthal plane, with a deviation of 18 ± 0.01% at a gantry angle of 90°. These results are in line with previous studies and are mainly attributed to the cylindrical geometry of the scintillator at the sensor end [4, 9].

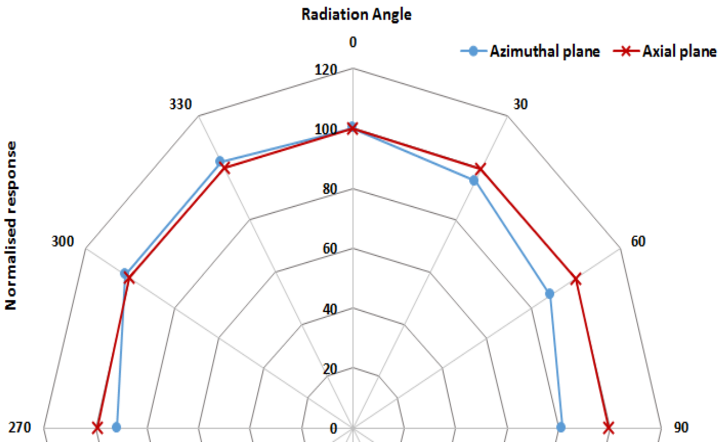

Fig. 8. The response of the OFS to different radiation angles, using axial and azimuthal configurations. All measurements were taken at 30° increments.

D. *Percentage depth dose and lateral dose measurements*

The PDD profiles obtained with the inorganic OFS compared to those measured with the microdiamond detector and the W1 plastic scintillator are shown in figure 9. It is clear from the figure that the OFS over-responded with respect to the microdiamond and the W1 for all field sizes. However, the percentage differences between the OFS and the microdiamond and the W1 decreased with a decrease in field size from 17.4 ± 0.04%, 8.3 ± 0.04% and 5.4 ± 0.06% for 10x10 cm^2, 4x4 cm^2 and 2x2 cm^2, respectively. As the Gd_2O_2S:Tb scintillator is not a water equivalent material ($Z_{eff} = 64$), the scattered radiation produced when the field sizes and/or the depth in phantom increases plays an important role in the overresponse of the OFS [15, 19, 20]

When compared to other studies that employed scintillating material with high Z numbers, however, our results showed higher discrepancies across the investigated field sizes [15, 20].This can be partly attributed to the Cerenkov radiation produced in the fibre itself and in the solid water phantom [21]. A 5% difference was reported by Martinez et al. (2015) for their YVO4:Eu^{3+} sensor when measuring PDD for a 3x3 cm^2 radiation field size with and without temporal filtration of Cerenkov at 10 cm depth [19].

At the same depth using the Gd_2O_2S:Tb OFS, a similar value (5.2 ± 0.07%) was calculated without filtering for Cerenkov radiation with a 2x2 cm^2 field compared to both the W1 and the microdiamond.

The depth dependence of the Cerenkov radiation was also reported by Glaser et al. (2014) in a theoretical and Monte Carlo simulation study. They concluded that for PDD measurements using a 6 MV photon beam the Cerenkov radiation emission overestimate the corresponding dose value by up to 5.6% after d_{max} [22]. These findings highlight the need for further investigation to quantify the overall contribution of Cerenkov radiation to the over response of the OFS.

Figure 10 shows the lateral dose profiles of field sizes ranging from 10x10 cm^2 to 2x2 cm^2 acquired with the OFS and the other reference detectors: the microdiamond and the W1 plastic scintillator. Only the cross-plane profiles were measured for this study.

There is good agreement between all detectors in the central and penumbral regions for all field sizes within the experimental uncertainties. There were, however, discrepancies between the OFS and the other detectors in the out-of-field regions across all field sizes. In the worst case, the OFS over-responded in the out-of-field measurements compared to the W1 by 19 ± 0.02% for the 10x10 cm^2 field. However, the percentage difference between the OFS and the other detectors in the out-of-field region decreased with the decrease in field size field size from 20% to only 5% for 10x10 cm^2 2x2 cm^2, respectively. The over-response of the OFS can partially be explained by sensitivity of the Gd_2O_2S:Tb scintillator to low energy scattered radiation (due to non-water equivalence).

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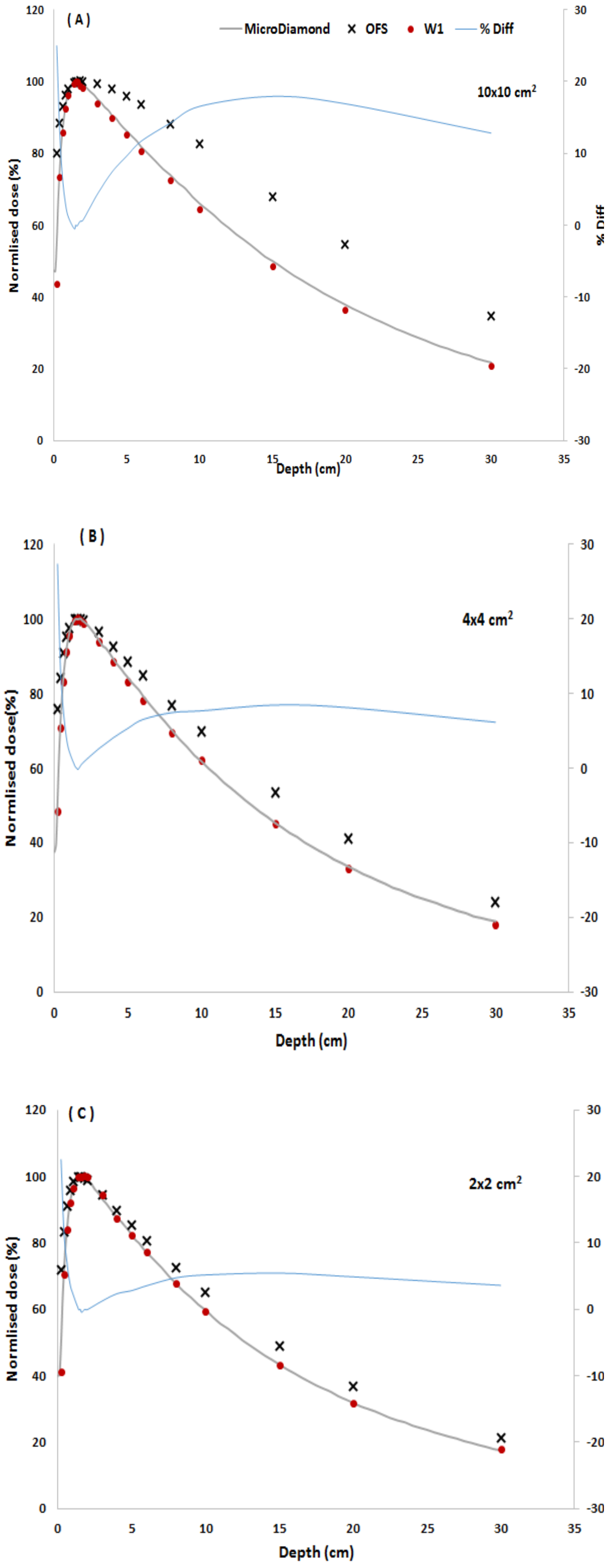

Fig. 9. PDD measurements obtained using the OFS (crosses) compared to the microdiamond (solid line) and the W1 plastic scintillator (dots) for (A) 10x10 cm^2, (B) 4x4 cm^2 and (C) 2x2 cm^2.

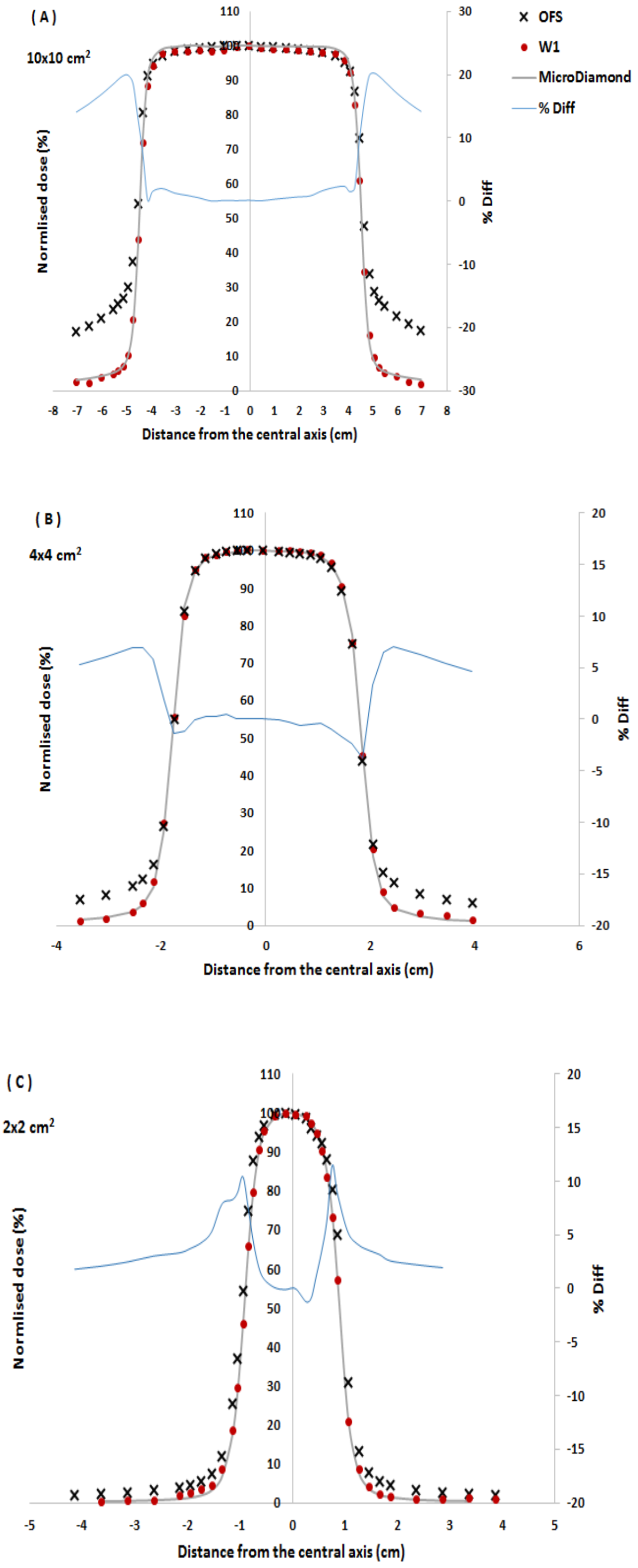

Fig. 10. Lateral dose profiles obtained using the OFS (black cross) compared to the microdiamond (solid line) and the W1 plastic scintillator (red dots) for (A) 10x10 cm^2, (B) 4x4 cm^2 and (C) 2x2 cm^2.

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V. CONCLUSION

In this study, the characterization of the Gd_2O_2S:Tb OFS with its Hamamatsu MPPC photon counting for external beam radiation therapy was investigated, and the performance of the system was compared with commercially available dosimeters. The OFS system demonstrated very good repeatability and reproducibility of the output signal with only a maximum of 0.17% and 1.00% differences from the average values, respectively. The results also show excellent linearity of the output signal with radiation doses, and the sensor response was independent of dose rate. However, further investigations are needed to address the discrepancies between the OFS response and the W1 when varying the DPP, especially at very high and very low DPP values. The sensor showed a small variation with different radiation angle in the axial plane. However, a strong angular dependence was observed when varying the incident radiation angle in the azimuthal plane, which was attributed to geometrical structure of the scintillator at the tip of the sensor. The presence of non-water equivalent material (Gd_2O_2S:Tb) caused the sensor to overestimate the dose when measuring PDDs and lateral dose profiles; this effect decreased with the decrease in field sizes. However, our results highlighted the need for further investigation to quantify the overall contribution of Cerenkov radiation to the over response of the OFS.

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REFERENCES

[1] G. J. Kutcher, L. Coia, M. Gillin, W. F. Hanson, S. Leibel, R. J. Morton, *et al.*, "Comprehensive QA for radiation oncology: report of AAPM radiation therapy committee task group 40," *Medical physics,* vol. 21, pp. 581-618, 1994.

[2] B. Mijnheer, S. Beddar, J. Izewska, and C. Reft, "In vivo dosimetry in external beam radiotherapy," *Medical physics,* vol. 40, 2013.

[3] A. Beddar, T. Mackie, and F. Attix, "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: I. Physical characteristics and theoretical considerations," *Physics in Medicine & Biology,* vol. 37, p. 1883, 1992.

[4] J. Fontbonne, G. Iltis, G. Ban, A. Battala, J. Vernhes, J. Tillier, *et al.*, "Scintillating fiber dosimeter for radiation therapy accelerator," in *Nuclear Science Symposium Conference Record, 2001 IEEE*, 2001, pp. 1707-1711.

[5] M. Guillot, L. Gingras, L. Archambault, S. Beddar, and L. Beaulieu, "Spectral method for the correction of the Cerenkov light effect in plastic scintillation detectors: A comparison study of calibration procedures and validation in Cerenkov light-dominated situations," *Medical physics,* vol. 38, pp. 2140-2150, 2011.

[6] A. M. Frelin, J. M. Fontbonne, G. Ban, J. Colin, M. Labalme, A. Batalla, *et al.*, "Spectral discrimination of Čerenkov radiation in scintillating dosimeters," *Medical physics,* vol. 32, pp. 3000-3006, 2005.

[7] S. O'Keeffe, M. Grattan, A. Hounsell, D. McCarthy, P. Woulfe, J. Cronin, *et al.*, "Radiotherapy dosimetry based on plastic optical fibre sensors," in *Fifth European Workshop on Optical Fibre Sensors*, 2013, p. 879418.

[8] P. Woulfe, F. Sullivan, and S. O'Keeffe, "Optical fibre luminescence sensor for real-time LDR brachytherapy dosimetry," in *Sixth European Workshop on Optical Fibre Sensors*, 2016, p. 99160T.

[9] S. O'Keeffe, W. Zhao, W. Sun, D. Zhang, Z. Qin, Z. Chen, *et al.*, "An optical fibre-based sensor for real-time monitoring of clinical linear accelerator radiotherapy delivery," *IEEE Journal of Selected Topics in Quantum Electronics,* vol. 22, pp. 35-42, 2016.

[10] M. Alharbi, M. Martyn, L. Chen, S. Gillespie, P. Woulfe, S. O'Keeffe, *et al.*, "Novel optical fiber sensors and their applications in radiotherapy," in *Optical Sensing and Detection V*, 2018, p. 106800Z.

[11] P. Stajanca and K. Krebber, "Radiation-induced attenuation of perfluorinated polymer optical fibers for radiation monitoring," *Sensors,* vol. 17, p. 1959, 2017.

[12] D. McCarthy, S. O'Keeffe, E. Lewis, D. G. Sporea, A. Sporea, I. Tiseanu, *et al.*, "Radiation dosimeter using an extrinsic fiber optic sensor," *IEEE Sensors Journal,* vol. 14, pp. 673-685, 2014.

[13] A. R. Beierholm, C. F. Behrens, and C. E. Andersen, "Dosimetric characterization of the Exradin W1 plastic scintillator detector through comparison with an in-house developed scintillator system," *Radiation Measurements,* vol. 69, pp. 50-56, 2014.

[14] E. E. Klein, J. Hanley, J. Bayouth, F. F. Yin, W. Simon, S. Dresser, *et al.*, "Task Group 142 report: Quality assurance of medical accelerators a," *Medical physics,* vol. 36, pp. 4197-4212, 2009.

[15] N. Martínez, A. Rucci, J. Marcazzó, P. Molina, M. Santiago, and W. Cravero, "Characterization of YVO4: Eu3+ scintillator as detector for Fiber Optic Dosimetry," *Radiation Measurements,* vol. 106, pp. 650-656, 2017.

[16] M. C. Aznar, C. E. Andersen, L. Bøtter-Jensen, S. Å. J. Bäck, S. Mattsson, F. Kjær-Kristoffersen, *et al.*, "Real-time optical-fibre luminescence dosimetry for radiotherapy: physical characteristics and applications in photon beams," *Physics in Medicine & Biology,* vol. 49, p. 1655, 2004.

[17] P. Carrasco, N. Jornet, O. Jordi, M. Lizondo, A. Latorre-Musoll, T. Eudaldo, *et al.*, "Characterization of the Exradin W1 scintillator for use in radiotherapy," *Medical physics,* vol. 42, pp. 297-304, 2015.

[18] A. S. Beddar, T. Mackie, and F. Attix, "Water-equivalent plastic scintillation detectors for high-energy beam dosimetry: II. Properties and measurements," *Physics in Medicine & Biology,* vol. 37, p. 1901, 1992.

[19] N. Martinez, T. Teichmann, P. Molina, M. Sommer, M. Santiago, J. Henniger, *et al.*, "Scintillation properties of the YVO4: Eu3+ compound in powder form: its application to dosimetry in radiation fields produced by pulsed mega-voltage photon beams," *Zeitschrift fuer Medizinische Physik,* vol. 25, pp. 368-374, 2015.

[20] M. Ramírez, N. Martínez, J. Marcazzó, P. Molina, D. Feld, and M. Santiago, "Performance of ZnSe (Te) as fiberoptic dosimetry detector," *Applied Radiation and Isotopes,* vol. 116, pp. 1-7, 2016.

[21] C. Penner, C. Hoehr, S. O'Keeffe, P. Woulfe, and C. Duzenli, "Characterization of a Terbium-Activated Gadolinium Oxysulfide Plastic Optical Fiber Sensor in Photons and Protons," *IEEE Sensors Journal,* vol. 18, pp. 1513-1519, 2018.

[22] A. K. Glaser, R. Zhang, D. J. Gladstone, and B. W. Pogue, "Optical dosimetry of radiotherapy beams using Cherenkov radiation: the relationship between light emission and dose," *Physics in Medicine & Biology,* vol. 59, p. 3789, 2014.

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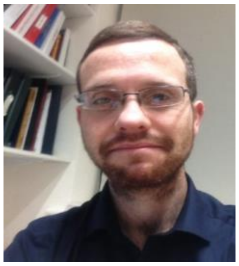

Sean Gillespie completed his B.Sc. in Experimental Physics from Maynooth University in 2006 focusing on Fabry-Perot interferometer research in his final year. He received a M.Sc. degree in Medical Physics in 2007 from the National University of Galway, where his research concentrated on the doses to organs at risk during gynaecological high dose rate brachytherapy. On completion of the M.Sc. Sean worked as the calibrations coordinator at Perfecseal Ltd in Derry city. In 2008 he joined the medical physics team at the Galway Clinic as the responsible physicist for Nuclear Medicine, PET-CT and CT. For the past several years Sean has worked mainly in the area of radiation oncology & in 2014 assumed the role of Senior Physicist for this area. His interests include, flattening filter free dosimetry, arc therapy and radiation treatment planning. He also has a keen interest in MRI Quality assurance which he is responsible for in the Galway Clinic. Sean's educational activities include facilitating the annual radiotherapy lectures & workshops for the NUIG M.Sc. in Medical Physics class, M.Sc. project supervision & mentoring of the 3rd year GMIT students placed in the Galway Clinic. Sean's Professional affiliations include membership of the Irish Association of Physicists in Medicine, Institute of Physics and Engineering in Medicine & full membership of the Irish College of Physicists in Medicine. He is also registered as a chartered scientist in the UK & with the Health and Care Professions Council.

Peter Woulfe received the M.Sc. degree in medical physics in 2003 from the National University of Galway, his thesis focused on the development of a novel Chest Phantom for Digital Radiography. On completion of the M.Sc. degree he has worked at the National Centre Laser Applications (NCLA) which led him to his current role as a Radiotherapy Medical Physicist in the Galway Clinic, progressing from a trainee physicist in 2004 to Medical Physicist Expert in 2009 and currently Principal Medical Physicist leading a team of five Physicists in the Clinic. In 2012, he has undertaken a part-time Ph.D. degree with the Optical Fiber Sensor Research Centre (OFSRC), University of Limerick, developing radiation dosimeters for monitoring patient doses received during radiotherapy for cancer treatment.

Pat McCavana received the B.S. degree in physics Queens University, Belfast, N. Ireland, in 1981 and the M.S. degree in radiation science from St Andrews University, Scotland, in 1990. From 1991 to 1995, he was a Clinical Scientist in the Radiotherapy Directorate in Ninewells Hospital, Dundee, Scotland. Since 1996 he has worked as a Medical Physicist at St Lukes Hospital, Dublin Ireland. His research interest includes radiation dosimetry and quality assurance in radiotherapy. Mr. McCavana a member of the Irish Association of Physicists in Medicine.

Dr Sinead O'Keeffe is a Royal Society – Science Foundation Ireland University Research Fellow at the University of Limerick. She graduated with BE (hons) in Electronic Engineering from the University of Limerick in 2003 and received her PhD in 2006 from the same institute, for the development of polymer optical fibre sensors for the sterilization industry. On completion of her PhD, she worked as a Marie Curie Research Fellow in the General Engineering Research Institute at Liverpool John Moores University, developing optical fibre sensors for monitoring UV and Ozone. She returned to the Optical Fibre Sensors Research Centre at the University of Limerick in 2008 and was awarded an FP7 Marie Curie Research Fellowship developing radiation dosimeters for monitoring patient doses received during radiotherapy for cancer treatment. She is currently a Royal Society – Science Foundation Ireland University Research Fellow leading a team that focuses on the development of optical fibre based sensor systems for the diagnosis, assessment and treatment of cancer tumours. She was Chair of the highly successful and recently completed COST Action TD1001 aimed at developing fibre optic sensor systems for reliable use in safety and security relevant applications in society. She is Member-at-Large of the IEEE Sensors Council for 2017-2020 and Vice-Chair of the IEEE Sensors Council UKRI Chapter (2016-2018).

Dr Mark Foley received the B.S. and Ph.D. degrees in Physics from the National University of Ireland Galway, in 2000 and 2004 respectively. In 2004, he was offered a 3 year Postdoctoral research position on the SFI funded Webcom-G project. Since 2007, he has been a full-time permanent academic with the School of Physics, National University of Ireland Galway. He established the Medical Physics Research Cluster in 2006 and a B.S. in Physics with Medical Physics in 2007. His research interests include applications of Monte Carlo codes in Radiotherapy and novel Medical Imaging systems with collaborators nationally and internationally. He is the Academic Director of the CAMPEP accredited MSc in Medical Physics, National University of Ireland Galway.