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ABSTRACT

The near-infrared radioluminescence and dosimetric properties of Yb-doped silica optical fibers, coupled with an optical detector prototype based on an avalanche photo-diode, were studied by irradiating the fibers with clinical beams generated by a Varian Trilogy accelerator. The performances of the system in standard and small field sizes have been also investigated comparing the output factor, percent depth dose and off axis ratio measurements of the prototypal dosimetric system with other commercial sensors.

The results demonstrated that the drawback due to the stem effect in Yb-doped silica optical fibers can be managed in a simple but effective way by optical filtering. These features, together with the accuracy and precision achieved by Yb-doped fibers in relative dose assessments make the device promising for in-vivo dosimetry studies in radiation therapy.

Keywords: Ytterbium, optical fiber, radioluminescence, Cerenkov, dosimetry, doped silica, radiotherapy

1. INTRODUCTION

In the last few years, there has been significant development of radiation therapy (RT) machines. Common features of these modern delivery systems are the modulation of the radiation beam, the use of radiation fields of small dimensions[1)] suitable for stereotactic treatments and the high conformation of the dose to the target with the consequent possibility of dose escalation and hypo-fractionation approaches[2)].

All these improvements could be a benefit for the patient, but at the same time open new challenges in terms of patient safety[3-5)], of treatment planning strategies, as well as of measurements[6-8)]. In fact, instruments and procedures that were suitable up to few years ago now may fail or provide results not sufficiently accurate[9)].

In this contest, scintillating optical fiber dosimeters could be particularly useful in various applications[10-16)]. Essentially, such dosimeter consists in a small scintillator that originates a radioluminescent (RL) signal when exposed to ionizing radiation. The scintillator is connected to an optical fiber acting as light guide to a suitable optical detector. In principle, an optical fiber dosimeter should enable the real time measurement of the dose rate in a specific point of the radiation field[17)]. The small dimensions could be exploited in small field dosimetry and in-vivo dosimetry. Moreover, the RL signal is unaffected by magnetic field, and so it could be particularly useful for dosimetry measurements in the new hybrid MRI-LINAC systems.

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Actually, the interest in these systems dates back to the early '90 [18], but it is only almost twenty years later that the first commercial system became available, the Exradin W1 by Standard Imaging[19]. The main reason of this long history was the need to face efficiently the intrinsic drawback of fiber optic dosimeters, which is the so-called stem effect. The stem effect is an additional luminescent signal due to the irradiation of the optical fiber that contributes mainly in terms of Cerenkov light. The stem effect is a spurious signal since it strongly depends on the irradiation conditions, typically the length of fiber directly exposed to the radiation beam and the direction of incidence of the beam on the fiber axis.

Various methods for the correction or subtraction of the stem effect have been proposed in the literature[20-24]. Unfortunately, all of them have showed some limits in various applications and therefore new solutions are welcome. In particular, it is clear that the attractiveness of fiber optic dosimeters would be greatly enhanced by employing a scintillation signal free from any spectral superposition with the spurious ones. We demonstrated that it is possible using a scintillator with an emission in the near infrared, that can be clearly distinguished from the stem effect emission occurring in the UV-VIS spectral region[25, 26]. This work aims to summarize the main findings of a recent comprehensive characterization of the dosimetric properties of Yb-doped silica optical fibers coupled with an optical detector prototype based on an avalanche photo-diode (APD) [27].

2. MATERIALS AND METHODS

2.1 The dosimetric system

A picture of the dosimetric system is shown in figure 1. The scintillator consisted in a small portion of Yb-doped silica optical fiber with diameter of approximately 200 µm and length 3 mm, prepared by sol-gel and "rod in tube" technique. Details of the synthesis procedure of doped-silica matrices are available elsewhere[28]. The doped portion was connected by fusion spicing with a 1 m long commercial optical fiber (Polymicro Technologies, AZ, USA).

A 15 m long multimode optical fiber extension (FT200EMT, Thorlabs Inc., NJ, USA) was used to connect the scintillating fiber, positioned in the treatment room where the medical linear accelerator (LINAC) was installed, to the optical detector localized outside the room. On the way to reach the detector, the RL signal was optically filtered by a series of two long-pass filters with a cut-on wavelength of 950 nm (FELH0950, Thorlabs) using an inline filter holder (B&W Tek Inc., DE, USA). SMA 905 type connectors achieved all the connections among the various optical components.

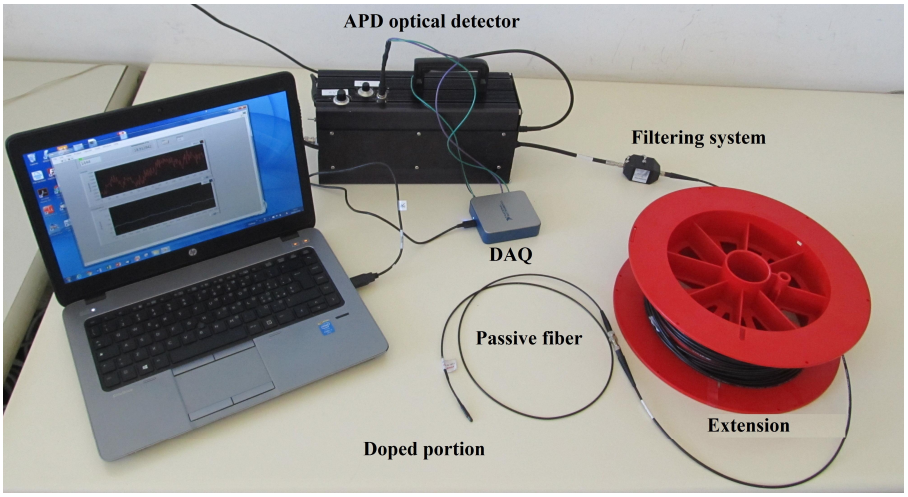

Figure 1. Picture of the fiber optic based dosimetric system.

The optical detector was a laboratory-made photon counting system based on a silicon APD (C309021S, Perkin Elmer Optoelectronics, Canada) operating in Geiger mode. The APD was characterized by a quantum efficiency (QE) curve extending beyond 1000 nm, with typical QE values of 13% at a wavelength around 975 nm, where the Yb^{3+} emission occurs. The package of the detector chip contained a light-pipe which fell within the active area of the detector, allowing efficient coupling with the optical fiber. The APD was cooled down to a temperature of approximately −19 °C by means of a two-stage Peltier thermoelectric cooling system. A specific circuit was implemented to quench and digitalize the APD breakdown pulse. A data-acquisition device (DAQ USB-6000, National Instruments, TX, USA) connected to a personal computer was finally used to acquire the signals of interest.

2.2 The irradiations

The irradiations of the fibers were carried out with 6 MV X-rays in Flattering Filter Free (FFF) modality, and 9 MeV electron beams generated by a Varian Trilogy TX accelerator (Varian Medical Systems Inc., CA, USA).

According to the specific experimental set up, the fiber was placed in a Solid Water™ phantom (GAMMEX rmi, WI, USA) or in a motorized water phantom (Blue Phantom, IBA Dosimetry GmbH, Germany). The various irradiation conditions and geometries used for the tests are described in detail elsewhere[27)].

A picture of the medical LINAC used for the irradiations and of a typical experimental set up is shown in figure 2.

Figure 2. Varian Trilogy TX accelerator and the motorized water phantom used for the irradiation of the fibers.

First, the general dosimetric properties of the system like sensitivity, reproducibility, dose response and dose-rate dependence were tested. Afterwards, the efficacy of the optical filtering approach for the stem effect removal was evaluated.

Finally, the performance of the system in standard and small field sizes were investigated, comparing the measurements obtained for the output factors (OFs), percentage depth dose (PDD) and off-axis ratio (OAR) of the prototype with those of other commercial detectors, including the Exradin W1 plastic scintillator.

3. RESULTS AND DISCUSSION

The dosimetric system, tested under clinical conditions, showed a satisfactory sensitivity, reproducibility, and a linear dose-rate response. A reliable dose evaluation was obtained independently of the dose rate and of the orientation of the impinging beam, clearly demonstrating that stem signal (and, more specifically, its Cherenkov component) was very efficiently suppressed[27].

Furthermore, the results showed a good agreement with reference dosimeters in terms of relative dose profiles and output factors. Examples of such measurements are shown in figures 3, 4 and 5. Figure 3 show the PDD obtained with the Yb-fiber compared with the reference one, measured by using a CC13 ionization chamber (IBA Dosimetry GmbH, Germany). The deviations between the two dosimeters were negligible at any depth and within the fiber reproducibility error (i.e. approximately 1%).

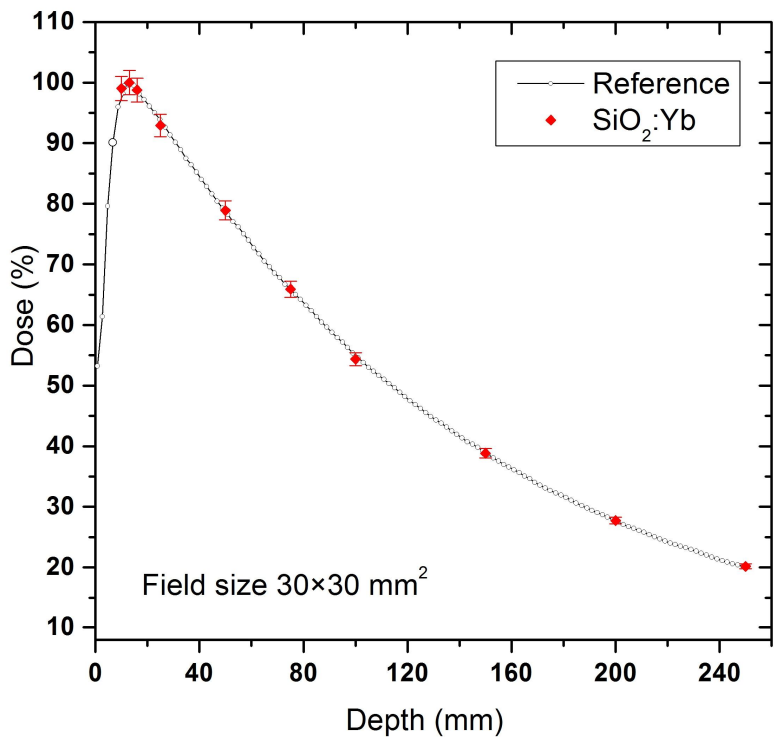

Figure 3. Example of Percentage Depth Dose (PDD) curve in water for a 6 MV FFF X-ray field with size 30x30 mm^2 obtained with the Yb-doped fiber compared with that measured by a CC13 ionization chamber, used as reference.

Figure 4 shows the OAR of the field 6x6 mm^2 obtained with the Yb-doped silica optical fiber and with the commercial scintillator Exradin W1. These results are compared with the reference profile obtained by means of radiochromic films EBT3. The data point of figure 4 were centred in the inflection point of the penumbra region.

The agreement between the prototype detector and the EBT3 film profiles was good for all of the investigated fields with maximum deviation in the high-gradient-region less than 5% and within the detector reproducibility in low-gradient-high and low-dose-regions. For the smallest field size investigated (i.e. the OAR of figure 4) the penumbra regions resulted slightly broader than the reference one, but they were in good agreement with the profiles obtained by the commercial fiber W1. It suggests that such differences could be due to a partial volume effect, having both the scintillators a similar length (3 mm). No significant dependence from the energy due to not water equivalence of the Yb-fiber was observed.

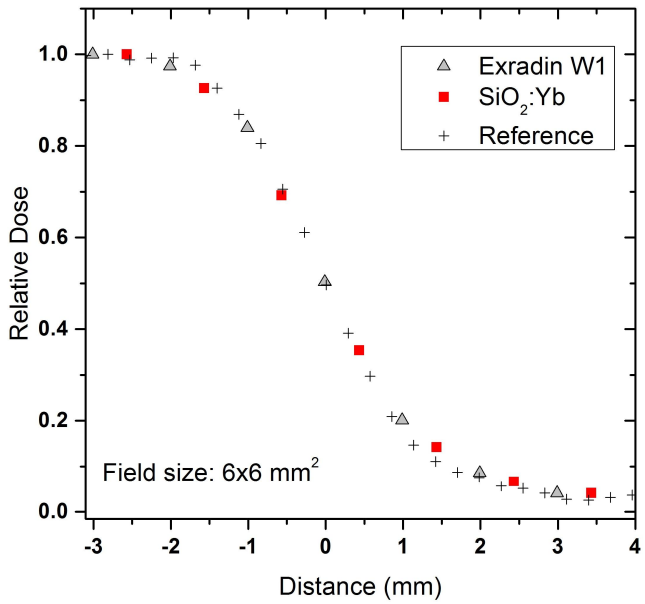

Figure 4. Example of off axis ratio (OAR) in water for a 6 MV FFF X-ray field with size 6x6 mm^2 obtained with the Yb-doped fiber and with the commercial scintillator Exradin W1, compared with the results of radiochromic films EBT3, used as reference.

Figure 5 shows the OFs of a 6 MV FFF X-ray beam measured with the Yb-doped fiber and compared with those obtained by the commercial scintillator Exradin W1. The agreement between the two detectors was within 1% independently of the field size.

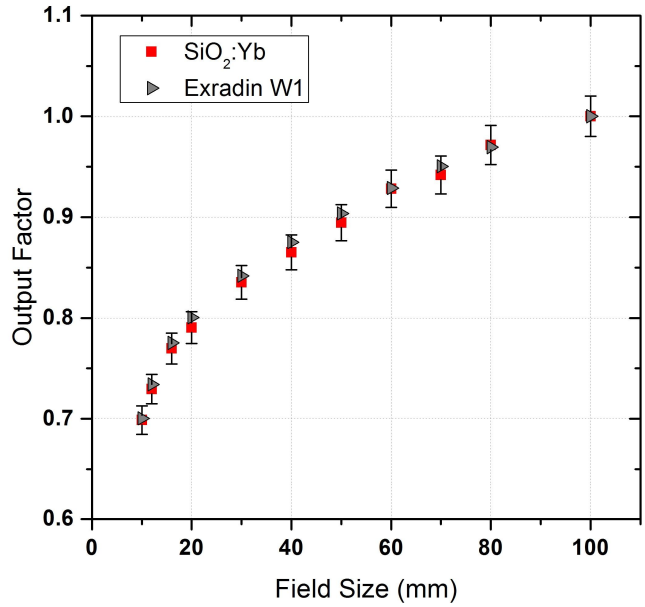

Figure 5. Output Factors (OF) of a 6 MV X-ray FFF beam measured with the Yb-doped silica fiber and compared with the results of the Exradin W1 plastic scintillator.

It is worth noting that the Exradin W1 proved to be a reliable tool for small field dosimetry applications such as RT beams commissioning and quality checks[1,29,30] thanks to its water-equivalence. However, the approach adopted for stem effect correction is very sensitive to the irradiation set up[31-34].

By contrast, Yb-doped silica optical fibers are not tissue equivalent, but they enable the complete suppression of the stem effect simply by optical filtering, without the need of any specific calibration procedure.

4. CONCLUSIONS

The results of this study demonstrated that the drawback due to the stem effect in Yb-doped silica optical fibers can be managed in a simple but effective way by optical filtering. The various tests carried out using small radiation field sizes and the most challenging irradiation geometries stated the robustness of the system in complex dosimetric scenarios. In fact, the response of the Yb-doped fibers was unaffected by the irradiation set up resulting independent of its orientation inside the radiation field, the angular beam incidence, the length of optical fiber directly irradiated, and of previously absorbed doses.

These features, together with the accuracy and precision achieved by Yb-doped fibers in relative dose assessments make the device promising for in-vivo dosimetry studies of radiotherapy treatments characterized by intensity modulation and steep dose gradients.

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