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Characterization of new materials for fiberoptic dosimetry

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Abstract. In this work we have investigated the radioluminescence (RL) characteristics of three materials (Mg2SiO4:Tb, CsY2F7:Tb and KMgF3:Sm) in order to determine whether they can be used as real time dosimeters in the the framework the fiberoptic dosimetry (FOD) technique. This technique is based on the use of scintillating materials coupled to the end of an optical fiber, which collects the light emitted by the scintillator during irradiation. Since usually the intensity of the emitted light is proportional to the dose-rate, the technique provides a reliable measuring method, which can be employed in radiotherapy treatments.

1. Introduction

In the last years the implementation of new radiotherapy treatments techniques based on the use of high dose rates delivered in small treatment regions claim for the development of dosimetry systems suitable for in-vivo and real-time dose measurement having high spatial resolution [1]. The use of diodes and thermoluminescence dosimeters (TLD) constitutes a well established method for in-vivo dosimetry. Disadvantages of diodes such as energy or position dependence respect to the irradiation beam and the impossibility of using TLD in real time dose assessment makes it necessary to investigate alternative dosimetry techniques. For this reason dosimetry techniques based on the use of MOSFET [2]-[5], radiochromic films [6]-[8], diamond detectors [9][10], and fiberoptic dosimetry (FOD) [11][12] have been investigated.

The FOD technique takes advantage of the radioluminescence (RL) or scintillating phenomena observable in several dielectric or semiconductor materials when they irradiated with ionizing radiation (X-ray, gamma ray, electrons, etc…). The basic idea of the FOD technique is to attach a small (1mm^3) scintillating material to the extreme of an optical fiber placed in the region of interest where the dose rate is to be measured. The optical fiber transports the emitted light outside the irradiation bunker where a light detector measures its intensity. Since the intensity of the RL emission is generally proportional to the dose rate then it is possible to obtain a real-time, absolute measurement of the dose rate after calibration.

The main characteristics of the FOD technique are: a) high spatial resolution, due to the small size of the RL detector; b) is a passive detector, there is no need for electrical connections; c) it is a robust system suitable for clinical use; finally d) on-line acquisition, this means real time dose rate measurement [13].

Several materials have been investigated in order to be used as scintillators in FOD, but aluminum oxide doped with carbon (Al_2O_3:C) has shown the most promissory results so far because of both its high efficiency (RL intensity vs. dose rate) with respect to other materials [14]-[16] and commercial availability (provided by Landauer Inc.). One of the drawbacks of Al_2O_3:C is the accumulated dose dependence. To overcome this problem a computational algorithm for real-time recalibration the RL signal and periodical optical resets have been proposed [15].

The main drawback of the FOD technique is the spurious luminescence (commonly known as stem effect) that adds to the RL emission from the scintillator. The stem effect is the result of the intrinsic luminescence of the optical fiber and the luminescence from the Cherenkov radiation. The main component of the stem effect in PMMA (polymethy methacrilate) optical fibers used in FOD is the Cherenkov radiation. This radiation is generated in an optical fiber when relativistic charged particles pass through the core at speeds greater than the local speed of light. It shows a λ^{-3} wavelength dependence, being significant at the blue region of the visible spectrum [17]. The intensity of the Cherenkov radiation depends on the length and position of the irradiated portion of the optical fiber with respect to radiation beam. For this reason its contribution is not univocally related to the dose rate at the position of the scintillator. It is necessary to remove the contribution of the Cherenkov radiation in order to have a precise estimation of dose rate.

Several methods have been proposed to eliminate or at least reduce the Cherenkov radiation. The simplest one consists in employing a second optical fiber (dummy) having no scintillator at its extreme, which is placed next to the fiber having the scintillating material (detector). During irradiation, the dummy collects the light from Cherenkov radiation. This light is simultaneously subtracted to the RL emission that comes from the RL detector. The only inconvenient of this method is the increased size of the detector system, which affects the spatial resolution (two optical fibers instead of one). This issue is of importance in radiotherapy treatments where high dose gradients are expected. Another simple method to reduce the Cherenkov radiation is optical filtering: a filter is used to eliminate the wavelengths outside the interval of wavelengths emitted by the detector. Since the Cherenkov light decreases as λ^{-3} the best solution is to choose a scintillator emitting in the red-near infrared region. Thus by employing a high-pass filter most of the Cherenkov light is eliminated. The third method to reduce the Cherenkov contribution is known as pulsed method. This technique is useful when a pulsed irradiation source is used, such as a linear accelerator (LINAC). This method takes advantage of the fact that the Cherenkov radiation emission is only observable during irradiation pulses and that in some scintillators the RL emission is still measurable between irradiation pulses. For this reason, if the RL is acquired during the time interval between irradiation pulses the contribution of the Cherenkov radiation can be eliminated. This method have been successfully employed in FOD technique based on Al_2O_3:C detectors under LINACs irradiation [13], [15], [18], [19].

The main goal of this work has been to find scintillating materials suitable to be used in the FOD technique. In particular, the dependence of the RL intensity as function of the irradiation time and the RL spectra of different RL materials have been compared to similar measurements obtained with Al_2O_3:C. Emission spectra have been obtained in order to determine whether the costless simple filtering method could be employed in each case. Percentage depth dose (PDD) obtained with the different scintillators have been compared with the PDD obtained with a standard ionization chamber (used as reference measurement).

2. Materials

Three different FOD probes were built for this work. In particular, terbium-doped silicate (Mg_2SiO_4:Tb), terbium-doped fluoride (CsY_2F_7:Tb) and samarium-doped fluoride ($KMgF_3$:Sm) were employed as scintillators. These materials were synthesized following the techniques described in refs. [20]-[22] respectively.

In order to fabricate the FOD probes pieces of 1mm3 were cut and glued to one of the ends of a plastic core optical fiber (PMMA, 980 microns diameter core, and 2 mm diameter outer jacket). The scintillators were optically shielded with an opaque, water resistant coating in order to avoid external light and humidity. A FOD probe was also fabricated using commercial Al_2O_3:C rods (1 mm diameter, 2 mm length, by Landauer Inc.). A fiber having no scintillator at its end was employed as a dummy.

Irradiation of the RL probes was performed in-situ (radiotherapy facility) employing a Theratron 80 60Co source, which renders 0.35 Gy min^{-1} at 5 mm water depth (80 cm SSD, source to surface distance) and an irradiation field of 10×10 cm^2. The RL signal from the FOD probes was measured by means of a Hammamatsu H9319 photon counting photomultiplier tube (PMT) having a sensitivity range between 300 and 850 nm.

All measurements were carried out in a water phantom (Civco MT-100) at room temperature under the following reference conditions, namely, 10×10 cm^2 field and 80 cm SSD. In all cases the end of the RL probe containing the scintillator (sensitive end) was placed at 5mm water depth and the fiber was perpendicularly oriented with respect to the beam axis.

The percentage depth dose (PDD) curve was determined at different depths in the water phantom by means of a manual depth dose apparatus (Civco, 0.1 mm resolution). PDD profiles were determined from surface down to 100 mm, under reference conditions. A PTW 30013 Farmer-type ionization chamber and a PTW UNIDOS E electrometer were used for reference dose-rate measurements. The stem effect contribution from the RL probes based on Mg_2SiO_4:Tb and CsY_2F_7:Tb scintillators were removed by subtracting the RL signal from the dummy probe measured in identical conditions. For the RL probe based on $KMgF_3$:Sm scintillators a high-pass Schott filter with a cutoff wavelength of 645 nm was used for stem effect removal.

The spectrum of the RL emission was measured by means of an Acton Research SP-2155 0.15 m monochromator with a resolution of 10 nm. The Hamamatsu H9319 photon counting placed at the exit slit was employed to detect the scattered light.

3. Results and discussions

Figure 1 shows the RL curves as function of time corresponding to the materials investigated in this work. It must be noted that a factor of 10 has been applied to both the RL curves of $KMgF_3$:Sm and the curve corresponding to the dummy. Although the samples have different transparency a reasonable comparison is possible since all the samples have the same volume (1 mm^3). As can be seen in figure 1 the rise time of the RL signal of the investigated probes reaches a maximum value very rapidly (tens of seconds). On the other hand, it takes almost a minute the Al_2O_3:C to reach its maximum intensity. It is worth mentioning that the RL signal from the dummy probe is always one order of magnitude lower than the RL signal from the different probes. The only exception is the $KMgF_3$:Sm probe, which shows a RL signal as intense as that of the dummy (stem effect). In all cases, the importance of the stem effect emission is enough to justify the use of removal techniques and the search for new scintillators materials having even higher RL efficiency.

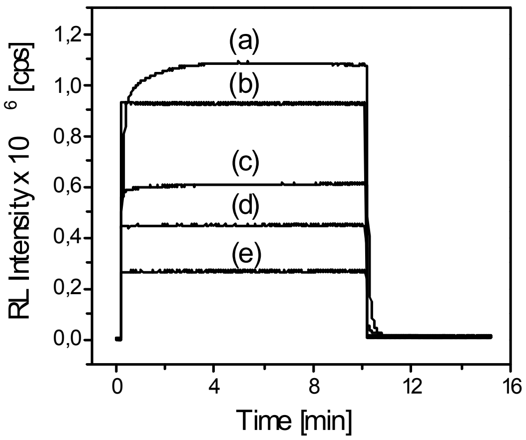

Figure 1. RL curves from Al_2O_3:C (a), CsY_2F_7:Tb (b), Mg_2SiO_4:Tb (c), $KMgF_3$:Sm × 10 (d) and dummy × 10 (e).

Figure 2 shows the emission spectrum of the different probes. The first spectrum (dummy) shows a maximum value near 400 nm and slowly decreases at higher wavelengths. The two next spectrums corresponding to the RL probes based on Al_2O_3:C and Mg_2SiO_4:Tb scintillators show an important overlap with the spectrum corresponding to the stem effect. This fact in precludes in these cases the use of the simple optical filtering technique for stem effect removal. However, these RL probes are in principle suitable to be used in LINACs employing the pulsed method to avoid the stem effect. This is not the case of the RL probe based on $KMgF_3$:Sm (figure 2(e)), whose emission spectrum shows a maximum value at 685 nm. By using a high-pass filter having a cutoff wavelength of 645 nm it is possible to reduce almost the entire contribution of the stem effect preserving the RL signal from the scintillator. However, its low RL efficiency makes this material not suitable for the FOD technique. The emission spectrum from the RL probe based on CsY_2F_7:Tb (figure 2(d)) shows a RL spectrum that makes possible the use of the simple optical removal technique in order to improve the RL signal/stem by employing, for instance, a long-pass filter with cutoff wavelength at 550 nm.

Figure 3 shows the comparison among the PDD curve obtained with the ionization chamber (solid line) and those from the different RL probes (scatter curves). All the PDD curves shows a maximum value at 5 mm water depth, as expected, except the RL probe based on CsY_2F_7:Tb that shows a maximum value at 16 mm water depth. It can also be seen in figure 3 that the PDD from the RL probe based on Mg_2SiO_4:Tb is similar to that corresponding to the ionization chamber. The PDD from the Al_2O_3:C RL probe shows a sub-response compared to the PDD curve from the ionization chamber. This result is consistent with the fact that the RL signal from this material varies as a function of accumulated dose during the successive measurements performed to obtain the PDD curve [15], [19].

The PDD from the $KMgF_3$:Sm-based RL probe shows a supra-response compared to the PDD curve from the ionization chamber. Investigations are in progress in order to determine whether the supra-response of this material is a dose-related effect. On the other hand, the PDD curve obtained with the RL probe based on CsY_2F_7:Tb shows an anomalous behavior compared to that obtained from the ionization chamber. The maximum value is shifted toward higher depths (16 mm) and the slope diverges from that of the PDD curve obtained with the ionization chamber. The origin of this unexpected behavior could be related to the particular physical process. Further basic research must be carried out in order to explain this scintillating phenomenon.

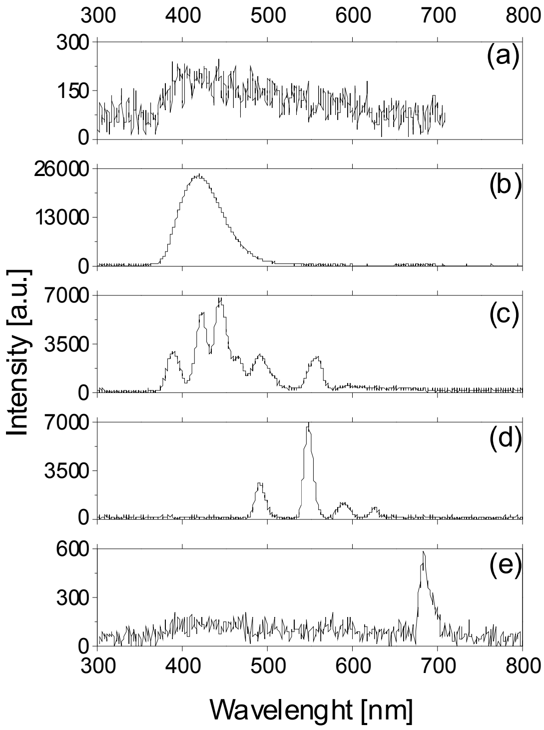

Figure 2. RL emission spectrum from (a) dummy (efecto stem); (b) Al_2O_3:C; (c) Mg_2SiO_4:Tb; (d) CsY_2F_7:Tb; and (e) $KMgF_3$:Sm.

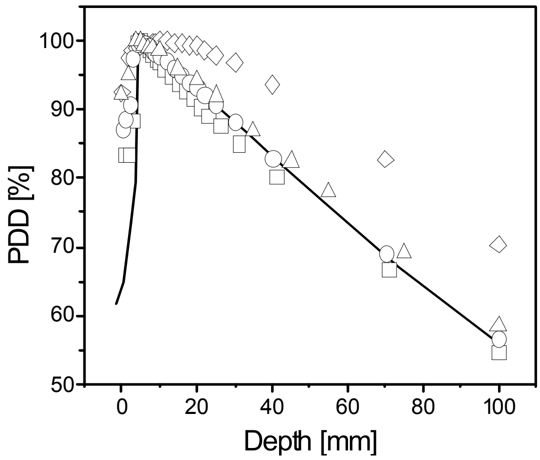

Figure 3. Percentage Depth Dose in water (PDD) from Al_2O_3:C (□), Mg_2SiO_4:Tb (○), CsY_2F_7:Tb (◊) and $KMgF_3$:Sm (Δ) compared to values obtain with a standard ionization chamber (solid line).

4. Conclusions

The optical fiber dosimetry is a promissory alternative technique for in-vivo dose assessment in real time. By means of this technique dose rate with high spatial resolution (lower than 1 mm) can be measured, as required by most recent radiation treatments. The FOD technique is mechanically robust and therefore suitable for routine handling by technicians in radiation treatment facilities.

In this work three materials have been investigated as possible scintillator to be employed in the context of the FOD technique: Mg_2SiO_4:Tb, CsY_2F_7:Tb and $KMgF_3$:Sm.

Terbium-doped silicate (Mg_2SiO_4:Tb) shows a high RL efficiency similar to that of the commercial compound Al_2O_3:C. Besides, the response of the Mg_2SiO_4:Tb shows no dependence on the accumulated dose. However, its application is limited to dosimetry in LINACs, where the pulsed method for stem effect removal is possible.

Samarium-doped fluoride ($KMgF_3$:Sm) has a poor RL efficiency, with an too low RL response/stem effect ratio.

Finally, terbium-doped fluoride (CsY_2F_7:Tb) has an anomalous RL response behaviour and it does not reproduce the absorption of energy in water, so this fluoride is not suitable for dosimetry in radiotherapy.

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