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Characterization of a fiberoptic radiotherapy dosimetry probe based on Mg_2SiO_4:Tb

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ABSTRACT

In this work the feasibility of using Mg_2SiO_4:Tb as a fiberoptic radioluminescent (RL) dosimetry probe for real-time dosimetry has been investigated for the first time. In particular, the stability of the RL signal after repeated use, the spectrum of the RL emission and the dose-rate response curve of a Mg_2SiO_4:Tb-based fiberoptic probe have been determined. The probe has been also used to obtain a percentage dose depth curve in a water phantom and its performance has been compared to that of a standard ion chamber. Besides, its absolute RL yield has been compared to that of an RL probe based on the commercial Al_2O_3:C phosphor.

1. Introduction

The increasingly sophisticated techniques employed today in radiotherapy claim for the development of dosimetry systems suitable for in-vivo, real-time dose assessment (Beddar, 2007). The recently established fiberoptic dosimetry (FOD) method offers the potential to fulfill these requirements. This technique is based on the use of an efficient scintillating material, which is placed at the point of interest either inside or close to the patient. During irradiation, part of the energy absorbed by the scintillator is re-emitted as light of characteristic wavelength. This effect is known as radioluminescence (RL). An optical fiber, to which the scintillator is coupled, transports the emitted light out of the irradiation room, where a suitable high-gain light detector collects the RL yield. Generally the intensity of the scintillation light is proportional to the dose rate, what makes the system suitable for dosimetry. Overall, the FOD technique shows interesting characteristics: a) the small size of the detector permits accurate dose measurements in regions of high dose gradients, b) the system does not rely on any external high-voltage bias, c) its rugged design makes it suitable for the routine tasks carried out by radiotherapy technicians, d) since the reading is obtained during irradiation, the FOD technique allows for in-vivo and real-time dosimetry (Justus et al., 2004).

Many materials have been investigated as possible FOD dosimeters: Cu^{1+}-doped quartz (Justus et al., 2004), plastic scintillators (Archambault et al., 2006), scintillating fibers (Frelin et al., 2006), Ce^{3+}-doped SiO_2 optical fibers (Mones et al., 2006), Tb^{3+}-doped fluorides (Marcazzó et al., 2007), carbon-doped Al_2O_3 (Aznar et al., 2005; Damkjær et al., 2008; Marckmann et al., 2006), etc. Among them Al_2O_3:C has undoubtedly become the most investigated one and many reports show that it is a promising material for in-vivo, real-time dosimetry. However, some dependence of its response as function of the accumulated dose requires corrections through an algorithm to obtain precise dose-rate assessment (Damkjær et al., 2008). Different commercially available thermoluminescent dosimeters, namely, TLD-100, TLD-200, BeO, etc., have been also investigated. However, their RL yield is too poor to be suitable for RL dosimetry (Erfurt and Krbetschek, 2002; Marcazzó et al., 2007).

The main drawback of the FOD technique has to do with the spurious luminescence arriving at the light detector, which adds to the RL from the scintillator. This light, which is known as stem effect, has two contributions. The first one is the intrinsic luminescence generated in the optical fiber by the ionizing radiation and the second one is the Cherenkov emission. The latter is usually the most relevant component of the stem effect and becomes more important in the blue region of the spectrum, since the intensity of the Cherenkov emission is proportional to the inverse of the third power of the wavelength (De Boer et al., 1993). Since the stem effect depends on the length and relative position of the portion of irradiated fiber with respect to the therapy beam, it is not univocally

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related to the dose rate at the sensitive end of the FOD probe. For this reason its contribution must be removed in order to obtain a measurement, which can be reliably linked to the dose rate.

Several methods have been put forward in order to get rid of the stem effect. The simplest method consists in using a second optical fiber without any scintillator at its extreme, say, a dummy fiber, which is placed in the same position as the FOD probe. During irradiation the dummy fiber only collects the spurious light and its signal is subtracted from that of the FOD probe in order to obtain the actual RL emission of the scintillator. Although very effective and robust, this method increases the final size of the probe, which precludes its use in those cases where high dose gradients are expected. Another removing method consists in simply filtering the light arriving at the light detector by means of optical filters, which cut off the spectral components of the stem effect. For this technique to be useful, the characteristic emission of the scintillator should be situated at longer wavelengths than the stem effect. A third technique for removing the stem effect, known as gated filtering, is only valid when the FOD probe is used for dosimetry in a linear accelerator (LINAC). LINACs emit radiation as a train of pulses, the dose rate being determined by the pulse frequency. Since the spurious luminescence is a short-lived effect, it is only important during the LINAC pulses. The gated filtering method consists in measuring the RL only during the time intervals between the radiation pulses. This technique has been successfully employed, for instance, to remove the stem effect in FOD probes in LINACs (Clift et al., 2002; Justus et al., 2004; Andersen et al., 2006; Damkjær et al., 2008).

Since the seventies Mg_2SiO_4:Tb has been well known for its high efficiency as thermoluminescent (TL) dosimeter (Bhasin et al., 1976). Recently, an optimal preparation of this TL phosphor has been reported, which shows the highest TL efficiency for this compound (Prokic and Yukihara, 2008). The optically stimulated luminescence (OSL) of Mg_2SiO_4:Tb has been also investigated (Mittani et al., 2008). In particular, Mg_2SiO_4:Tb fulfills the preliminary requirements to be taken as a promissory OSL dosimeter. Other luminescence properties of Mg_2SiO_4:Tb, which could be of interest in dosimetry, such as its radioluminescence (RL), have been never explored.

In this work the feasibility of using terbium-doped magnesium silicate (Mg_2SiO_4:Tb) as a FOD RL dosimeter has been investigated for the first time. In this context, a Mg_2SiO_4:Tb-based FOD probe has been fabricated and its response under ^{60}Co irradiation at a radiotherapy facility has been studied. In particular, its RL yield has been obtained and compared to that of a FOD probe based on commercial Al_2O_3:C crystals. Besides, the spectrum and stability of the RL emission have been determined. Finally, the FOD probe has been commissioned to obtain the PDD curve in a water phantom and the result has been compared to that obtained in identical conditions by means of a standard ionizing chamber.

2. Materials and methods

The terbium-doped silicate samples used in this work were developed by M. Prokic at the Institute of Nuclear Science, Vinca, Belgrade (Mittani et al., 2008). They were sintered for 1 h at 1660 °C in air, under slow heating rate. The resulting phosphor then was crushed and sieved in grains sized between 75 and 200 microns. By cold pressing the resulting polycrystalline material was shaped into pellets 4 mm diameter and 0.80 or 0.40 mm thickness, which were sintered under the same conditions as during the preparation of the polycrystalline phosphor. The final sintered pellets are opaque and very hard.

In order to fabricate the FOD probes 1 mm^3 pieces were cut from a Mg_2SiO_4:Tb pellet 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 scintillator was optically shielded with an opaque, water resistant coating in order to avoid external light. Identical FOD probes were fabricated by using commercial (Landauer Inc.) Al_2O_3:C rods (1 mm diameter, 2 mm length).

Irradiation of the RL probes was performed in-situ (radiotherapy facility) employing a Theratron 80 ^{60}Co source, which renders 0.35 Gy min^{-1} at 5 mm water depth (80 cm SSD, source to surface distance). The RL signal from the FOD probes was measured by means of a Hammamatsu H9319 photon counting photomultiplier tube (PMT) having sensitivity between 300 and 850 nm. In order to remove the spurious contribution due to the stem effect emission a second optical fiber probe having no scintillating sample at its end was used. This dummy probe was placed close to the FOD probe during the experiments and its signal was subtracted from the FOD probe signal in order to obtain the actual RL yield. In all cases, the signal of the dummy probe was found to be less than 10% the signal of the RL probes.

Unless specified otherwise 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 (source to surface distance). In all cases the end of the FOD probe containing the scintillator (sensitive end) was placed at 5 mm 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 (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 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. The sample was placed at the entrance slit and irradiated by means of the ^{90}Sr source, which was situated 1 cm away from the sample.

3. Results and discussion

Before carrying out the experiments both the Mg_2SiO_4:Tb and Al_2O_3:C FOD probes were dosed (stabilized) up to 100 Gy at the ^{60}Co source. According to the literature at this dose level the traps involved in the TL of both materials reach saturation (Yukihara et al., 2003; Prokic and Yukihara, 2008). It is expected that after this pre-irradiation process possible transient behavior of the RL emission related to partial trap filling could be reduced.

In Fig. 1 the RL curves of the Mg_2SiO_4:Tb and Al_2O_3:C FOD probes measured under reference conditions are shown. As can be seen, the maximum RL intensity is of the same order for both probes. However, in the case of the Mg_2SiO_4:Tb probe the raising time, say, the time necessary for the RL signal to reach its maximum value, is appreciably shorter. In fact, while the raising time for the Mg_2SiO_4:Tb probe is of the order of 1 s, the corresponding value for the Al_2O_3:C probe is approximately 10 times longer. Although useful, this result provides only a rough comparison of the RL yield between both kinds of probes, by taking into account that the shape of the samples glued at the end of the optical fiber is slightly different in each case. Besides, the light collection efficiency is also possible different, since the commercial Al_2O_3:C rods are transparent, while the Mg_2SiO_4:Tb pellets are opaque.

In order to study the response stability after repeated use of the Mg_2SiO_4:Tb probe, its RL emission has been recorded during eight consecutive irradiation cycles. The exposure time was 60 s and the lapse between irradiations 120 s. Each time the RL intensity has