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Radioluminescence results from an Al_2O_3:C fiber prototype: 6 MV medical beam

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ABSTRACT

The Investigations of this article focus on the response of an Al_2O_3:C radioluminescence (RL) prototype for medical dosimetry in a 6 MV photon beam. The prototype can be configured using two types of detectors coupled to fiber-optic cables - single crystal ($1 \times 1 \times 2\,mm^3$) and droplets (in two grain sizes, 38 and 4 μm, molded in r = 0.5 mm, l = 200 μm). By using the appropriate filters in addition to time gating it is possible to remove disturbance present during irradiation: the stem effect. Pre-irradiation of the dosimeters to a dose of 300 Gy made the memory effects in Al_2O_3:C negligible, so as to not impair the dosimetric properties of the system. The key findings are that the system is suitable for small field beam dosimetry, while giving overall good dose response in other features (i.e., beam profile, dose rate - FF and FFF modes). The results show that our prototype can be used for real time dose rate assessment in medical photon dosimetry without many correction factors. The 4 μm RL measurement results are in excellent agreement (i.e. below 1%) with the dose delivered according to standard beam data.

1. Introduction

Evolution in technology has changed radiation therapy to a highest degree of sophistication and complexity that needs to be accordingly translated to radiation protection and dosimetry. Among the innovations on treatments, flattening filter free (FFF) beams are now commonly available with new standard linear accelerators. These beams give recognized clinical advantages such as the reduced beam-on times for high dose per fraction treatments [1]. Additionally, the new systems are also capable of delivering high focalized dose distributions using small field sizes to the tumor, decreasing lateral doses to health tissues. A small field is generally defined as having dimensions smaller than the lateral range of the charged particles that contribute to the dose deposited at a point along the central axis, i.e. <3 cm^2 [2,3].

Flattening filter free (FFF) beams and dynamic multi-leaf collimation bring new challenges on dosimetric aspects linked to field size, penumbra and quality assurance (QA) [1]. Dosimetry in small fields, for instance, is complicated [4], because most of the reference conditions parameters such as stopping power ratio, perturbation correction, fluence and gradient corrections are not applicable [5].

A lot of effort has been dedicated on finding suitable dosimetric solutions for new and sophisticated radiotherapy treatments. Among the attempts, real-time detectors are strong candidates for the job. Real-time detectors are capable of measuring the total dose during a treatment session, but are in principle also capable to measure the time-resolved intra-fraction dose delivery (dose rate), which provides additional useful information in some situations [6].

Real-time dosimeters include ionization chambers, diodes [7], metal-oxide semiconductor field effect transistors (MOSFETs) [8], scintillation detectors [9,10], and electronic portal imaging devices (EPIDs) [11]. Current real time techniques have inherent limitations, such as narrow dynamic range, energy dependence, processor dependence, variation in optical density or limited resolution and very high cost for hardware and labor related [12,13]. Improvement of existing systems, as well as new solutions, is the subject of several on-going studies.

In the last two decade, optical fiber systems based on organic and inorganic materials appeared as a solution for in vivo radiotherapy dosimetry, with many advantages over currently employed clinical dosimetry systems. There are a number of different materials

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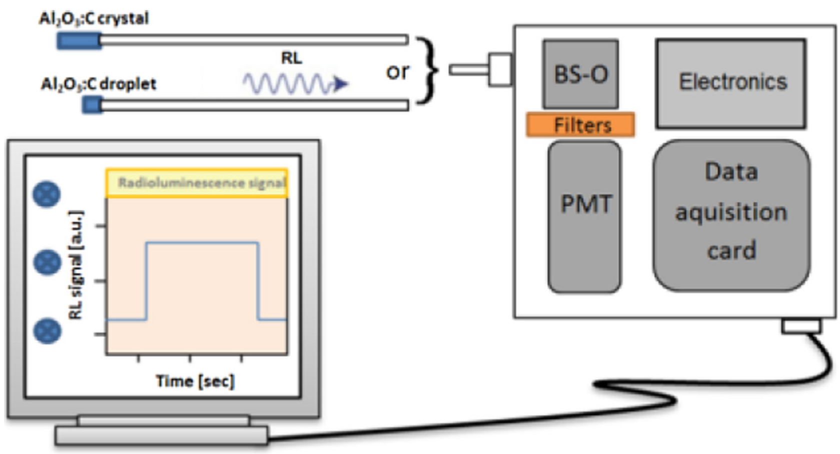

Fig. 1. Sketch of the RL dosimetry system as described in the text. Two choices of RL detectors (crystal or droplet) can be coupled to the system via an optical fiber, that guides the signal thought an optical arrangement (beam splitter and focusing lenses, called BS-O), reaching the PMT tube after passing a set of filters. The signal is then processed by the DAQ and is acquired by a computer, with Labview software.

evaluated for punctual real time dose rate measurements. Among them is worth citing plastic scintillators [14–19], Ce, Cu, Ge, Eu and Yb-doped optical fibers [10,20–24], organic scintillators [25,26] and solid state dosimeters, such as BeO [27], LiF [16] and Al_2O_3:C [28,29].

Al_2O_3:C optically stimulated dosimeters have been introduced in medical dosimetry of low and high LET beams [30,31] in the past 15 years. In addition, Al_2O_3:C detectors can also be used as real time dosimeters, because the material emits radioluminescence (RL) during irradiation of which the intensity is proportional to the beam's dose rate [6]. Radioluminescence is light generated by free charge (electrons and holes induced by ionizing radiation) recombining at luminescence centers. In the case of Al_2O_3:C two RL components are present: 28 μs ('fast' component, with main emission at 520 nm) and 35 ms ('slow' component, with main emission at 420 nm) [32,33]. Dosimetric characteristics of Al_2O_3:C radioluminescence were already demonstrated in some previous works [28,34–39].

The protocol used in this article proposes to perform dosimetry using solely the RL from saturated (i.e. pre-irradiated) Al_2O_3:C droplets and crystals attached to optical fibers, avoiding optical stimulation, which disturbs the equilibrium of trapped charges in the crystal [35]. In this approach, Al_2O_3:C is used as a scintillator exploiting the slow component of the RL signal.

The present work investigates the performance of Al_2O_3:C RL + fiber detectors [40] using 6 MV photon beams. Results about stem effect removal, dose rate dependence in FF and FFF modalities, linearity with dose, output factors (from $1 \times 1\,cm^2$ up to $30 \times 30\,cm^2$), and dose profiles are presented and compared with those of standard dosimetry systems (ionization chambers and a commercial optical-fiber scintillator [31]). In addition, we discuss accuracy and precision of the RL measurements when using two different droplets (crystal sizes) vs. single crystal.

2. Materials and methods

2.1. Dosimeters and readout system

The three active dosimeters used in this work are based on 1) a $1 \times 1 \times 2\,mm^3$ single crystal ('CG'), 2) a droplet (r = 0.5 mm and l = 200 μm) with average crystal size of 38 μm ("38 μm"), [41] and 3) a droplet (r = 0.5 mm and l = 200μm) with average crystal size of 4 μm ("4 μm"). In all cases we used a 15 m long PMMA (GH4001) optical fiber "glued" to the dosimeters using a photocuring polymer [41]. The bare end of each fiber was polished and glued to a SMA connector. The detectors and optical fibre were covered with a water-equivalent material to prevent light exposure.

Radioluminescence of Al_2O_3:C is known to be affected by memory effects and after-glow phenomena, as observed previously by various authors [42,43]. These effects, if not properly taken into account, may represent potential source of systematic errors in dose assessments by RL measurements. As observed by Andersen and colleagues [35], a proper pre-irradiation of the material enables to achieve a constancy of the RL sensitivity, provided that the Al_2O_3:C crystal is not perturbed by optical stimulation (i.e. by OSL measurements).

On the basis of these evidences, all our dosimeters were pre-saturated once with a dose of 300 Gy using a $^{90}Sr/^{90}Y$ source to fill deep traps that compete with recombination centers and the readout system was solely used in RL mode.

To assess the calibration curves of each dosimeter + fiber we previously measured the radioluminescence signal (RL_{ref}) versus reference absorbed dose (D_{ref}) with various doses of a 6 MV photon beam, 10 cm × 10 cm field size, Source Surface Distance (SSD) of 100 cm, at 10 cm depth in a PMMA slab phantom.

The readout system prototype [37] consists of an optical apparatus with focusing lenses, dichroic mirror to guide the luminescence from the optical fiber; two sets of filters, used separately, where the first (F1) rest in two 7.5 mm Hoya U-340 (Edmund Optics) for OSL measurements [29], and the second, (F2) rest in two 425 nm Hard Coated Broadband Bandpass Interference Filter (Full Width-Half Max FWHM of 25 nm, Edmund Optics) used in RL measurements. Luminescence was measured using a bialkali photomultiplier tube (PMT) (P30USB, Sens-TechTM). Data acquisition and control were performed using a NI USB 6341 card (National Instruments, USA) and a Labview program. The system is sketched in Fig. 1.

In the following graphs, some results are compared with their "residuals", defined as the difference between the observed/measured value and the predicted/reference value.

2.2. Irradiations

The external beam irradiations were performed at two different hospitals: (1) Algemeen Stedelijk Hospital (UZBrussel, Aalst/Belgium), using a 6MV beam Elekta Compact system (Elekta AB, Sweden) and; (2) University Hospital "Maggiore della Carità" (Novara, Italy) using a 6 MV x-rays beam generated by a Varian Trilogy TX accelerator (Varian Medical Systems Inc., CA, USA). Both the LINACs were calibrated following the IAEA TRS-398 code of practice (IAEA 2000) to obtain an equivalence of 1 cGy/1 mon-