A Multi-Sensor dosimeter for brachytherapy based on radioluminescent fiber sensors

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ABSTRACT

High-precision dosimeters are needed in brachytherapy treatments to ensure safe operation and adequate working conditions, to assess the correspondence between treatment planning and dose delivery, as well as to monitor the radiation dose received by patients. In this paper we present the development of a multi-sensor dosimeter platform targeted for brachytherapy environments. The performance of different scintillating materials response is assessed. The emission bands of most common scintillator materials used in ionizing radiation detection are typically below 550 nm, thus they may be prone to stem effect response. To avoid this effect we propose the use of scintillators with longer wavelength emission. Samples of neodymium doped glasses are evaluated as new infrared radioluminescent scintillators for real-time dosimeters, namely lithium lead boron silver (LLB4Ag) and lithium bismuth boron silver (LBiB4Ag) glasses. Their response is compared with the response of organic scintillator BCF-60 with a 530nm response.

Keywords: dosimetry, radioluminescence, brachytherapy.

1. INTRODUCTION

An effective brachytherapy treatment depends on the accuracy of radiation delivery to the target volume. The effectiveness may be assessed by the use of proper dose measurement devices, preferably in situ and in real time. Scintillators have been highlighted as an interesting alternative for the measurement of the absorbed dose [1]. The scintillating response of these materials is excited by ionizing radiation, where the absorbed energy is re-emitted as light. This process is already found in applications such as gamma cameras in medical diagnostics, neutron and high energy particle physics experiments, x-ray security, nuclear cameras, computed tomography and radiation detectors, among others [1, 2]. The success of scintillator materials is linked to their higher energy resolution and excellent linearity in high temperature environments, ultrafast rise times, adequate mass absorption coefficients and tissue-equivalent characteristics [2, 3]. Nowadays there are already scintillating fiber-optic dosimeters (SFOD) intended to be used for *in vivo* real-time dosimetry in brachytherapy [3]. However, Cerenkov radiation and fluorescence generated by irradiation of the optical fiber constitutes a common and unwanted background signal, usually referred to as stem effect, by the direct action of the ionizing radiation with charged particles that passes through a medium with a velocity greater than that of light [4]. The radiation from Iridium pellets (^{192}Ir), an isotope commonly used in brachytherapy, is able to produce secondary electrons in irradiated materials with sufficiently high energies for Cerenkov radiation production in optical fiber, within a peak spectral range between 400 to 480 nm [5]. Since the Cerenkov radiation is proportional to $1/\lambda^3$, where λ is the wavelength of the Cerenkov light, the use of long wavelength scintillators is a method of avoiding the influence of stem effect on the detected signal [5], by spectral separation of the contributions due to stem effect and scintillation. Although Al_2O_3:C and plastic scintillators have been shown to be promising materials for developing fiber optic dosimetry systems suitable for clinical applications, they emit radiation in the wavelength range < 550 nm, which means that they may be affected by stem effect [6]. Hence, the search for new compounds possessing appropriate radiation-induced luminescence is on-going [7]. It is known that glass samples doped with rare earth ions have infrared emission [8-10].

The use of SFOD made of a water-equivalent material for dose measurements should have a small sensitive volume combined with a high spatial resolution and emission of light proportional to the absorbed electron and gamma dose rate [4, 11], properties offered by optical fibers as thin, flexible, robust and lightweight dose transducers, also being immune to electromagnetic and chemical interferences [5, 9]. The use of PMMA optical fiber as intrinsic sensors for monitoring high doses of gamma radiation for industrial and nuclear applications is well known, as well as the real-time monitorization of low doses of ionising radiation, such as x-ray, gamma rays, alpha and beta particles [12].

In this work, we describe a multi-sensor set-up targeted to the evaluation of real-time optical response of SFOD dosimeters, using both radioluminescent infrared and visible scintillating sensing head probes.

2. MULTI-SENSOR DOSIMETER BASED ON SCINTILLATING FIBERS

The multi-sensor dosimeter allows direct and quasi-simultaneous reading of the absorbed doses in several field points. The radioluminescence signal measurement is multiplexed allowing the mapping of the dose imparted at different field locations, in conditions similar to those of brachytherapy procedures. The use of two types of scintillators, emitting visible and near infrared range light, is intended to validate new materials response, as well as assessment of stem effect minimization. The scintillating materials used in this work are described in the next section.

2.1 Radio-luminescence fiber sensors

The dosimeter probe is made of a radioluminescent material coupled to an optical fiber that collects and transports radiation to a remote light measuring device. For the infrared emission range, several neodymium doped glasses were tested, and different dopant molar concentrations used, in order to study the influence of neodymium molar concentration in radioluminescent intensity, with dopant concentrations ranging from 0 to 4 mol%. Glasses were prepared by melting raw chemicals in crucibles for about one hour in an electrical furnace at temperature of 950 ºC, by employing the quenching technique. The developed neodymium doped glasses probing samples (LLB4Ag and LBiB4Ag) were produced at INESC TEC and tested at the local Oncology Institute (IPO-Porto) where they were irradiated in similar conditions to those of Brachytherapy, with a Nucletron Microselectron v2 ^{192}Ir source. Irradiation time was five seconds. The test probe dimensions were: diameter of 0.5-1.5cm, thickness between 0.31-0.41cm) coupled to silica optical fiber that transports radiation to a remote light measuring device. Additionally samples made with a commercial organic scintillator (BCF-60, Saint-Gobain), with 1 mm diameter, and lengths up to 1.71 cm were also tested, for comparison of the resultant radioluminescent signal, attached to both PMMA and silica fibers.
The silica fiber used in the dosimeter probes was a low –OH multimode silica fiber (Thorlabs) with 1000 µm core diameter, 30 cm length, terminated with SMA connectors. The plastic fiber was a PMMA fiber (RS Electronics) with 1000 µm diameter. Dosimeter samples of whole bare fibers were also prepared for stem effect estimation.

2.2 Set-up of multi-sensor dosimeter

The SMA terminated SFOD probes were linked to another low–OH multimode silica fiber with the same diameter and 10m length, either directly through an SMA-SMA connector, or interfaced with a Fiber Optic Multiplexer (8x2 channels, Avantes). Index matching gel (Thorlabs) was used to maximize the optical coupling of the radioluminescent signal to the transmitting optical fiber. The radioluminescent signal was detected both in the visible (320-1100 nm) and infrared (800-1700 nm) spectral windows (Fig.1), with different detectors (PDF10A and PDF10C from Thorlabs; MPPC from Hamamatsu). The femtowatt photo-receivers combine a selected ultra-low noise Si photodiode with a specially designed trans-impedance amplifier offering extremely high gain. The electrical signal was acquired with a NI DAQ USB-6351. Control and signal processing were performed with the aid of Labview software (National Instruments).

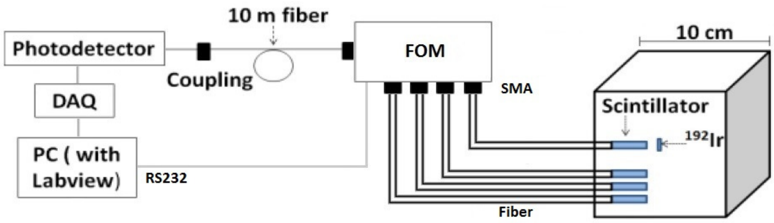

Figure 1 - Schematic diagram of the developed prototype placed within a PMMA phantom, in order to make feasible irradiation of radioluminescent samples with ^{192}Ir.

3. RESULTS AND DISCUSSION

Preliminary tests of radioluminescence Nd doped LLB4Ag and LBiB4Ag glasses probes response was performed in the visible and near-infrared region, for exposures of five seconds to the ^{192}Ir source. Figure 2 summarizes the results obtained for visible light, and include the response of bare fiber (Cerenkov/stem effect), with the PDF10A detector. The stem effect shows up with a mean value of 0.280±0.009V, a background signal adding up to the radioluminescence acquired, and present in all probe measurements done with the PDF10A photoreceiver. The maximum collected radioluminescence emitted by unpolished LBiB4Ag-2Nd is about 45% of that coming from BCF-60, which includes the radiation from stem effect, which is about 32% of the total radioluminescence collected when BCF-60 was attached to the silica fiber. The obtained value for stem effect is within the range established by Proulx et al [13], which says it can account for up to (72±3)% of the signal under clinically relevant conditions. The signal from the polished sample LLB4Ag-1Nd, about 59% of that coming from BCF-60, suggests that the collected signal improves with polishing. The coupling of infrared radioluminescent signal can also be increased by polishing the scintillating material.

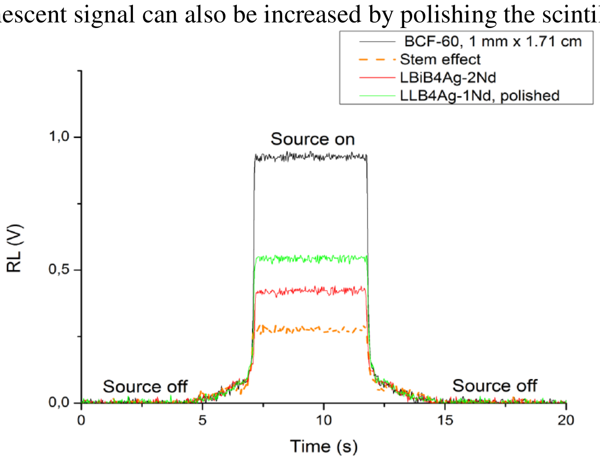

Figure 2 - Radioluminescence of BCF-60, unpolished LBiB4Ag, Polished LLB4Ag-1ND and Stem effect detected with PDF10A (320-1100nm).

In figure 3a infrared response of the Nd dopes glass samples obtained with the PDF10C photodiode is shown: there is no radioluminescence present when neodymium was not added to LLB4Ag host glass, as expected from the $1/\lambda^3$ dependence of Cerenkov radiation; also, there is a similar behaviour for LLB4Ag and LBiB4Ag samples. As hinted from the previous results, and according to fig. 3b, there is also radioluminescence in the visible range, and the signal obtained when neodymium has a concentration of 0 mol% is due to stem effect.

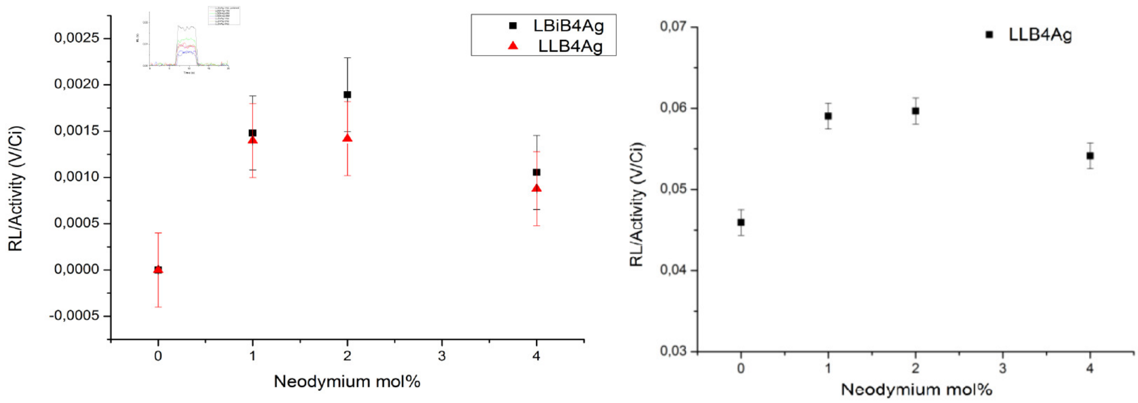

Figure 3 - Radioluminescence divided by activity versus neodymium mol%, for a) LLB4Ag and LLBiB4Ag detected with a PDF10C (800-1700nm). The inset show a NIR Radioluminescence smoothed with the average of 20 adjacent points and b) LLB4Ag detected with a PDF10A.

Fig. 3 also shows that there is an optimum neodymium concentration for radioluminescent emission. This concentration seems to lie between 2-4 mol%. After that optimum concentration there is a decrease of radioluminescent emission due to quenching mechanisms, which seems to be in accordance with reference [14]. The behaviour of doped neodymium glasses in near-infrared, can be explained, since neodymium fluorescence is known to correspond to wavelengths around 867 nm, 1065 nm, 1330 nm and 1835 nm, respectively. Therefore it seems that radioluminescent signal comes from

neodymium, and this is detected with both photoreceivers, since these radioactive transitions lie in the bands of detection of both photodiodes. It is expected that the scintillator barely disturbs the radiation field due to its mass absorption coefficients which is water-equivalent in a wide range of energies.
Multi-channel dosimeter results will be presented for simultaneous reading of dose in different configurations, such as dose distribution in a PMMA phantom, stem effect elimination performance when using visible radioluminescent probes. The PMMA phantom allows multiple dosimeters positioning in a radial arrangement, with a radioactive source at its center point. Also, dose measurements are being performed with an ionisation chamber to validate the linearity of dosimeters response, and will be compared with those obtained by the described multi-channel dosimeter.

4. CONCLUSION

The radioluminescence of Neodimium doped LLB4Ag and LBiB4Ag glasses is being studied as radioluminescent materials for accurate in real time dose measurements in Brachytherapy. These materials promise Cerenkov radiation free signals, since stem effect is not detected in the infrared wavelengths. In conclusion, the read-out system for dosimetry with plastic scintillators combines the advantages of the plastic scintillator dosimetry, such as water-equivalence, direct reading and high spatial resolution, with a parallel, computer-controlled read-out. The uncertainty due to Cerenkov light can be reduced by using reference fibers or reduce the by using a 10 m long light fibers, in which the Cerenkov light will be more attenuated in some wavelength ranges than the information signal.

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