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Radiochromic and radiofluorogenic 3D solid polymer dosimeter: initial results for high doses

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Abstract. The complexity of dose distributions has increased with the advent of intensity modulated radiation therapy (IMRT). For that reason, experimental measurements using 3D dosimeters with high spatial resolution are required to check the delivered dose. In this study a new 3D solid polymer dosimeter with absorbance and fluorescence responses to radiation is presented. Measuring fluorescence instead of absorbance improves the spatial resolution and eases the read out of the dosimeter. The proposed dosimeter is tissue-equivalent and can be moulded in any shape by a controllable and fast photopolymerization process.

1. Introduction

Modern radiotherapy requires complex dose distributions; therefore, there is an increasing demand for a high spatial resolution system suitable for dose verification to ensure treatment quality [1]. Over the last years, 3D dosimetry systems have been developed for this purpose [2]. They may be classified into polymerizing dosimeters or radiochromic dosimeters, which use magnetic resonance imaging (MRI) [3] or optical computed tomography (CT) [4] as readout systems. These dosimeters change chemical properties upon irradiation [5]. While polymerizing dosimeters consist of a gel matrix that polymerizes with radiation [6], radiochromic dosimeters consist of a gel, plastic or silicone matrix with a radiation sensitive dye that changes color with radiation exposure [7, 8].

It is important to remember that a dosimetry system is not only the dosimeter itself but also the readout technique used for extracting the dose information after irradiation. Oldham *et al* [9] applied both techniques (MRI and CT) to the same gel dosimeter and they obtained a higher resolution for CT. Besides that, MRI scanners have significant disadvantages like its cost and availability, and they may be susceptible to several uncertainty sources like field homogeneity and temperature [10]. These uncertainties are well understood and can be compensated. However, there are still issues concerning the material properties of the gels. It is known that the radiation induced cross-linking of the gel is highly dependent on its oxygen level, pH, and temperature, just to mention a few parameters. For those reasons CT is more commonly used [11].

Some problems of the CT scan are the light scattering and the acquisition time. Gel dosimeters require the use of a container, which adds scatter artifacts in the read out due to reflections [12]. Therefore, the scattering may be reduced by using a solid dosimeter that does not need a holder. Solid dosimeters also avoid the diffusion problem present in gel dosimeters, which causes blurring of the dose distribution image over time. For some systems, the acquisition of the image may be time consuming since current CT readout systems require scanning of several slices while the sample rotates to acquire

data at different angles. For example, the 3D scan of the commercially available PRESAGE™/OCTOPUS™ dosimetry system needs 15 slices and takes 8-9 minutes per slice [13]. This gives a total scanning time of 2 hours, followed by a computer intensive image reconstruction. A simple, *in-situ* and fast reading of the dosimeter would facilitate the use of the 3D dosimeter in a clinical basis.

A way to increase the scanning speed is by using scanners based on charge-coupled device (CCD) cameras, since it is possible to obtain a complete 2D image in one go [11]. This technique can be used to measure the fluorescence [14] instead of the attenuation as the CT does. We have developed a 3D readout based on a black and white CCD camera. Detecting small signals is difficult when measuring the absorbance (or attenuation) in the dosimeter; however, measuring fluorescence allows us to use color filters to ensure that the vast majority of the signal comes from the dye in the sample.

In this paper we present a sensitive, soft-tissue equivalent and moldable 3D solid polymer dosimeter that is not only radiochromic but also radiofluorogenic. The underlying mechanism involves the conversion of a non-fluorescent dye molecule into a fluorescent form when incorporated into a rigid polymeric matrix and irradiated. The imaging of the dose distribution is obtained by measuring the fluorescence intensity, which can be recorded using a conventional digital camera. This gives a higher accuracy, a higher spatial resolution and a faster read out, compared to the current commercially available 3D dosimetry systems.

2. Materials and methods

2.1. The dosimeter

We use a poly(ethylene glycol) diacrylate matrix (PEGDA-575 g/mol) containing pararosaniline leuco dye [15]. The radiation chemistry involved in the transformation from leuco dye to dye is presented in figure 1 [16]. This polymer enables the solidification of the material through a photopolymerization process. We use diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO) as photoinitiator.

The dosimeter can be molded in any shape by light of approximately 400 nm, which does not affect the dye. This is a controllable and fast process that only takes up to 10 minutes. After curing, the dosimeter can be removed from the mold. This property could open up for a significant number of clinical applications relative to making patient-like geometries, or using it as a thin 2D dosimeter (film) for the radiation field verification as a quality control test.

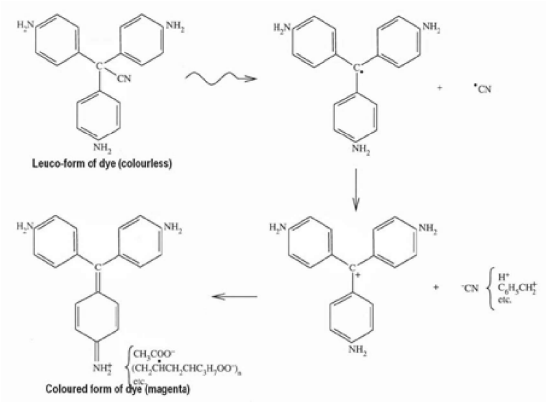

Figure 1. Chemical reaction of the leuco dye due to radiation.

2.2. The readout system

Optical fluorescence tomography is used for read out of the dose distribution in the dosimeter (figure 2) [17]. The dosimeter is submerged in an index matching fluid tank and excited with a green laser. Pictures of the fluorescent emission are taken with a CCD black and white camera to get the 2D dose distribution. 3D information is obtained by moving the sample through the light sheet while taking pictures.

The scanning speed is up to 2 millimeters per second, so the total scanning of the dosimeter is finished within minutes, which avoids problems of chemical changes during scanning. This technique allows having an *in-situ* reading and the device is easy to use. These characteristics would facilitate its use in the clinic.

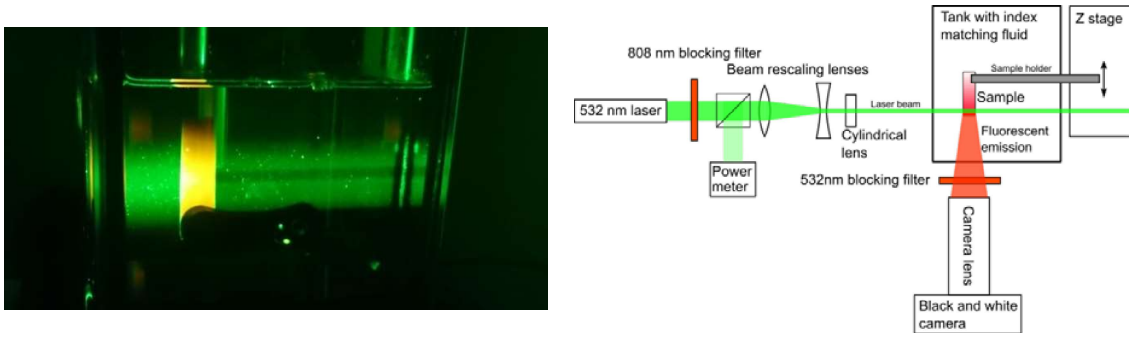

Figure 2. Picture of the dosimeter inside the index matching fluid tank and scheme of the readout system.

2.3. Irradiations and measurements

Irradiations were carried out in a ^{60}Co gamma source with a dose rate of 139.3 Gy/min. The uncertainty on the delivered dose is 1.3%. Absorbance was measured with a Shimazdu UV-2700 spectrophotometer. Fluorescence is excited with a 532 nm Nd:YAG laser, and measured with an Ocean Optics QE6500 spectrometer.

3. Results and discussion

A slide of 1 mm thickness is cured between two glass plates to ensure the best optical quality and irradiated up to 1 kGy in steps of 100 Gy. Normalized absorbance and fluorescence spectra as function of the dose are shown in figure 3. The results show that the fluorescence response is strong enough to be used. In figure 4 we present the fits of the responses with the absorbed dose for different parts of the spectrum. While the absorbance response is linear with the dose, the fluorescence response is exponential in overall and linear for the clinical dose range.

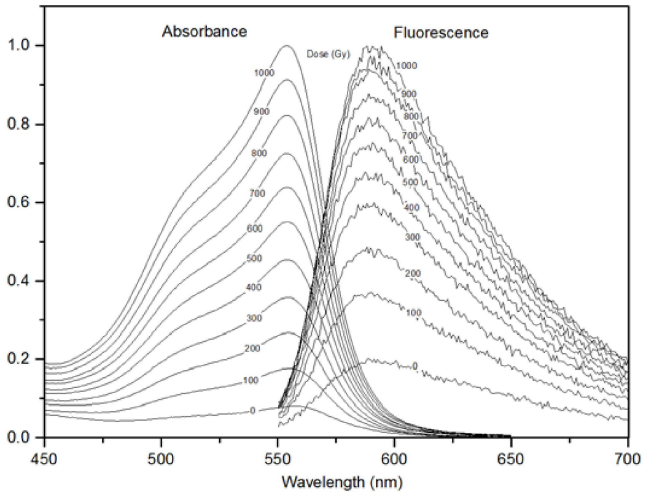

Figure 3. Normalized absorbance and fluorescence spectra.

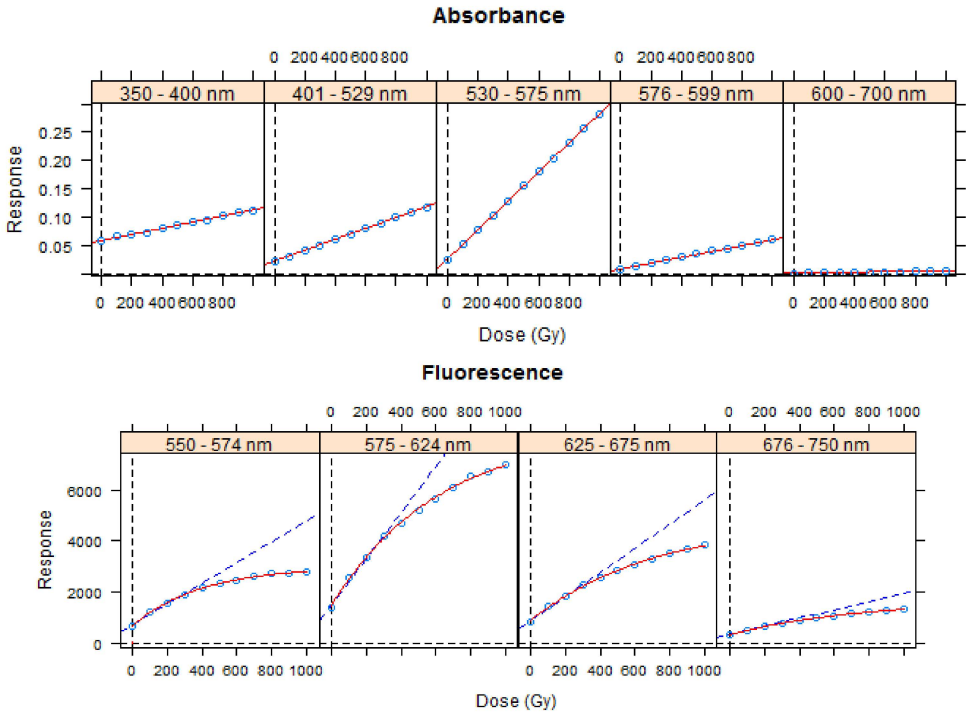

Figure 4. Absorbance and fluorescence fits as function of the absorbed dose.

4. Conlusions

We have developed a passive solid dosimeter that is tissue equivalent, can be molded in the desired form and does not need a container. The dosimeter responds to irradiation in the same way as radiochromic films (oxidation of a leuco dye) but we have established a polymer matrix for this dye that allows us to measure not only the absorbance of the material but also its fluorescence. The main difference with current 3D solid polymer dosimeters is the readout technique. While current 3D dosimetry systems mainly use CT to extract dose information, we can measure the fluorescence, which potentially is a faster and more sensitive method. The response range of this dosimeter is very high (up to 1 kGy), but future studies will focus on optimizing the dosimeter at low doses for its clinical application.

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