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Absolute calibration for film dosimetry

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Recent results in the field of film dosimetry demonstrated that the Green–Saunders equation, a solution of the logistic equation describing phenomena of kinetics of chemical reactions, is the absolute calibration function for all radiochromic film types. Taking advantage of the new opto-electronics-based radiochromic film reading method, which allows real-time measurements of the spectral response of radiochromic films, we confirm that the film darkening is ruled by the Green–Saunders equation independently both from the reading instrument or the choice of the observable used for the calibration. In order to demonstrate it, we exposed an XR-QA2 Gafchromic film to ^{90}Sr/^{90}Y beta rays up to 1400 mGy. Film spectra are recorded in real-time. The calibration is performed by means of two analytic methods: evaluation of the integral under the curves from 500 nm to 645 nm and evaluation of the intensity at 570, 600 and 643 nm. Experimental data fit to the Green–Saunders equation for both methods.

Keywords: Dosimetry; radiochromic film; absolute calibration function.

1. Introduction

Film dosimetry plays a fundamental role in many fields of applied radiation physics. Film badge dosimeters have, to date, been used as reliable personal and environmental dosimeters for monitoring cumulative radiation dose. Radiochromic films (RCFs) have the advantage, with respect to silver-halide films, of being self-developing. Radiochromic films are mostly used for quality checks in radiation therapy and in particular for measurements of dose delivered to the phantom and for the reconstruction of Percentage Depth Dose (PDD) curves.[1–2] The use of RCFs in brachytherapy applications is reported in many works in the literature.[3–4] RCF’s use in radiation hardness application is also widespread;[5–6] operations such as beam centering and measurements of beam profile and radiation dose are fundamental in Radiation Hardness Assurance (RHA) tests.[7–8] RCFs are perfectly fit for these applications.

RCFs show an increasing darkening with the increase of the radiation dose. To perform the calibration, a set of films must be exposed to radiation of known doses; a relationship between the doses and the corresponding level of darkening must therefore be established. This last can be evaluated by means of scanners, densitometers or, in general, any instrument capable of providing lighting and corresponding light reading. Dedicated software allows the evaluation of the Pixel Value (PV) of a film digitized with flat-bed scanners. The PV represents a measure of the films' darkening. Densitometers provide direct measurements of the absorbance A(λ) (or optical density), defined as:

$$A(\lambda)\frac{I_0\,(\lambda)}{I(\lambda)}, \tag{1}$$

where $I_0(\lambda)$ and $I(\lambda)$ are the light intensities of the unexposed and exposed films at fixed wavelength, respectively. We recently developed and patented a new opto-electronic based instrumentation for the optical spectroscopy of RCFs; it also allows real-time dosimetry by means of measurements of the RCF darkening.[9,10]

The problem of finding a unique relationship between the dose and the film's level of darkening, namely a unique calibration equation, is widely discussed in the literature.[11–13] The traditional approach consists in finding the mathematical function that best fits the experimental data; exponential and polynomial functions are mostly used. Recently, we proposed the absolute calibration equation for all RCF types.[14,15] This equation, the Green–Saunders equation, has a general validity since it is the physical law that describes the phenomenon of the film darkening. The fitting parameters of this function have therefore a precise physical meaning related in particular to the film's contrast and dynamics. In order to discuss this topic, results of the exposure of an XR-QA2 Gafchromic film to a ^{90}Sr/^{90}Y beta source are shown in the following. This film was read in real-time by means of the new opto-electronic based instrumentation, and optical spectra were analyzed.

2. New Experimental Setup for Real-Time Measurements

The new RCF's real-time reader is based on opto-electronic instrumentation. It consists of a bundle of optical fibers, a halogen light source and a broad-band spectrometer. A scheme of principle is shown in Fig. 1; more details on this method can be found in Refs. 9–10.

The bundle of optical fiber is made of seven fibers. Six fibers transport the light form the light source up to the RCF; one fiber collects the light after it interacted with the RCF and sends it back to the spectrometer. Measurements have been performed with a 36 MBq ^{90}Sr/^{90}Y beta source with a dose rate of 2 Gy/h in the position of the RCF. A XR-QA2 Gafchromic film was used. XR-QA2 films, mostly used for radiology quality assurance tests, are sensitive in the dose range 1–200 mGy. Figure 2 shows the intensity light spectra (recorded at fixed doses) in the wavelength range of maximum sensitivity of XR-QA2 films, namely between 500 nm and 645 nm.

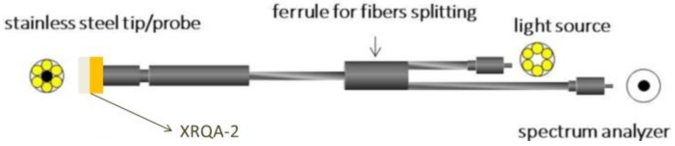

Fig. 1. Opto-electronic based instrumentation for the real-time reading of RCFs.

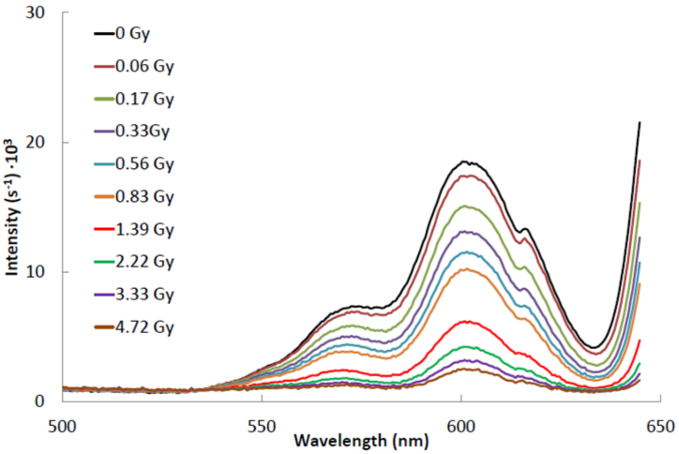

Fig. 2. Optical spectra recorded in real-time at different doses.

The radiation-induced darkening results in a lowering of the intensity of the spectra. More than one analytic method for the dose calibration can be adopted. We will discuss two of them: integral under the curve in a fixed wavelength range and intensity at fixed wavelength value.

3. Absolute Film Calibration

The dose calibration of the XR-QA2 film is performed by evaluating the integral I_v (in the wavelength range 500–645 nm) under the curves of Fig. 2, as shown in Fig. 3.

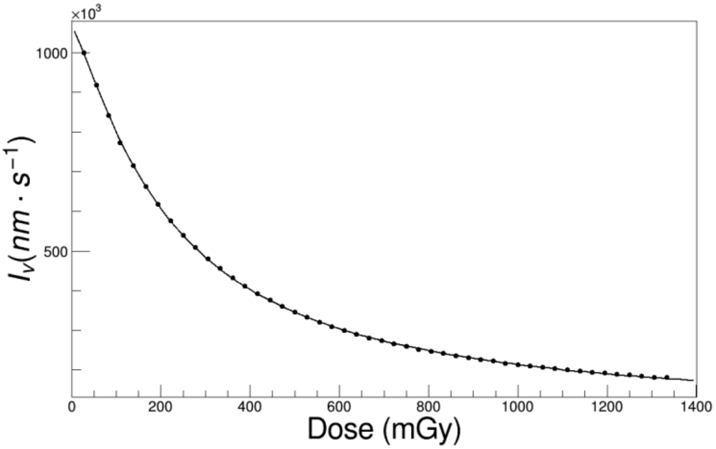

Fig. 3. Calibration of XRQA-2 Gafchromic films by means of evaluation of the integral under the curves of Fig. 2. The solid line is the Green–Saunders equation.

The solid line is the best fit of the experimental data. Its equation, also known as the Green–Saunders equation, has the following expression:

$$y = y_{min} + \frac{y_{max} - y_{min}}{1+10^{\beta(log x_0 - log x)}}, \qquad (2)$$

where x is the dose and y is the observable used for the calibration (e.g. the integral I_v for the calibration of Fig. 3). The terms y_{min} and y_{max} fix the film dynamics, β is the film contrast and x_0 is the abscissa of the inflection point of the sensitometric curve. The Green–Saunders equation belongs to the family of logistic functions describing in particular phenomena of kinetics of chemical reactions, including the phenomenon of radiochromic processes. If the calibration is performed by recording the intensity of the curves of Fig. 2 at fixed wavelength values, the trend of experimental data is the same of Fig. 3, namely the data lie on Green–Saunders curves. Figure 4 shows this calibration for 570, 600 and 643 nm.

Table 1 reports the values of the best fit parameters for the four choices of the observable used for the calibration. The best fit of Green–Saunders curves to experimental data of Figs. 3 and 4 was evaluated by means of the least-squares (χ2) method for which values of reduced χ2 less than 1 were obtained.

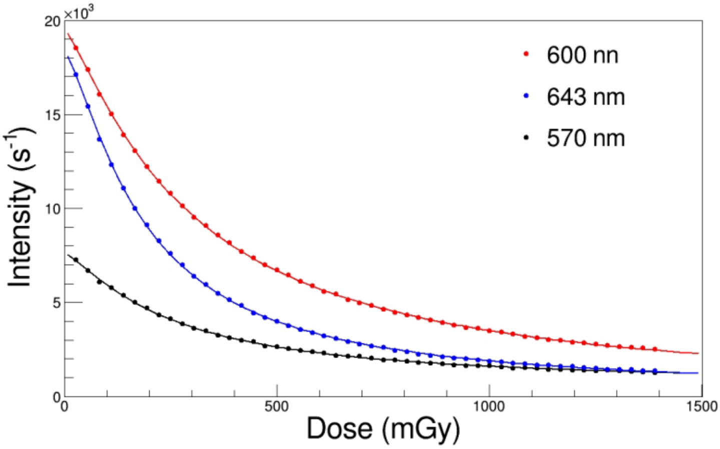

Fig. 4. Calibration of XRQA-2 Gafchromic films obtained by recording the intensity of the curves of Fig. 2 at the following wavelength values: 600, 643 and 570 nm. The solid lines are Green–Saunders equations.

Table 1. Best fit parameters for different choices of the observable used for the calibration.

Fitting parameter	Iv	570 nn	600 nm	643 nm
y_{min}	$(8.3\pm0.2)\cdot10^4$	556±41	115±55	180±32
y_{max}	$(106.7\pm0.4)\cdot10^4$	$(7.6\pm0.5)\cdot10^3$	$(19.5\pm0.6)\cdot10^3$	$(18.3\pm0.1)\cdot10^3$
B	-1.24±0.01	-1.27±0.02	-1.23±0.01	-1.36±0.01
D_0 (Gy)	223±1	251±3	298±1	188±1

4. Conclusion

The new opto-electronic based method for the reading of RCFs has several advantages compared to traditional methods. In addition to providing the new feature of real-time dosimetry with RCFs, it allows spectral characterizations of RCFs. The phenomenon of the film darkening is clearly modeled. It results in a progressive lowering of the intensity of light spectra. The dose calibration can be performed by evaluating the integral under the curves (see Fig. 3) or by evaluating the intensity at fixed wavelength values (see Fig. 4). The experimental data lie on Green–Saunders equations, in any case. These equations belonging to the family of logistic functions describe a class of phenomena including radiochromic processes. We already demonstrated the validity of this equation as the calibration equation for B3 films, EBT3 and HDV-2 Gafchromic films analyzed with commercial scanners.[14] In this work, we exposed an XR-QA2 Gafchromic film to beta rays from ^{90}Sr/^{90}Y source. The reading of the darkening of the film was performed in real-time by means of the new opto-electronic based method. Since the Green–Saunders equation rules the physical law of the film darkening, these are independent of the RCF type and on the reading method. As a result, the experimental data of calibration curves perfectly fit the Green–Saunders equation. The fitting parameters have an important physical meaning, being related to the film dynamics and contrast. Since the response of XR-QA2 Gafchromic films is strongly dependent on the wavelength, the analysis of the observables for the calibration leads to different performances in terms of dynamic range and sensitivity. The evaluation of the integral in the wavelength range 500–645 nm is a good compromise among the observables studied.

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