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Original paper

A novel method for EBT3 Gafchromic films read-out at high dose levels

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ABSTRACT

In this work, we report on a novel approach for measuring the dose absorbed by the EBT3 Gafchromic™ films exposed to 1 MeV electron beam and 250 kV X-rays in the range 0.5–100 Gy. Although EBT3 is specifically designed to obtain best performance for applications where the maximum dose is less than 10 Gy, there are certain clinical applications requiring dose ranges well above this value. In order to cover wider dose ranges, further models characterized by a thinner sensitive layer and/or different chemical composition have been released. Another method exploiting the three-channel flatbed scanner to delay the saturation point of EBT3 has been also reported. The technique proposed here, aimed at extending the sensitivity of the EBT3 film to high doses up to 100 Gy while ensuring a low dose uncertainty, is based on a broadband analysis of the absorption spectrum of the film in response to irradiation. By combining a wavelength-based approach with the monitoring of two characteristic peaks of the EBT3 absorption spectrum, we demonstrated the capability of measuring the dose in the range 0.5–100 Gy with an experimental uncertainty below 4% for doses lower than 5.52 Gy and below 2% for higher dose levels. Finally, through a dynamic fitting procedure integrating the two aforesaid approaches, a total uncertainty lower than 4%, including both the experimental and fitting errors, was achieved in the whole range 0.5–100 Gy. These results are promising in view of a potential application of this technique in the field of clinical dosimetry at high dose levels.

1. Introduction

Over the time, the need for powerful tools for a precise and effective measurement of the radiation dose in several fields, such as clinical radiotherapy and radiology, has promoted the development of various dosimetry systems, whose accuracy plays a fundamental role in the success of a clinical treatment. Among these, radiochromic film (RCF) dosimetry, based on the self-developing process occurred upon irradiation, has gaining importance as one of the most widespread strategies in radiotherapy treatment verification and quality assurance [1,2]. RCF's working principle is based on the change of its optical properties upon irradiation. RCFs show an increased darkness as consequence of the absorbed dose. This effect is explained considering the polymerization of diacetylene dye monomers after irradiation [3,4]. In addition to a high spatial resolution, generally common to film dosimetry, this response mechanism to radiation provides some attracting properties, like relatively weak energy dependence in a broad range of beam qualities used for radiation therapy and near tissue equivalence [5,6]. Due to their characteristics, RCFs represent a suitable tool for dose measurement in radiation fields with high dose gradients, as attested by a large number of clinical, industrial and research dosimetry applications [2], including brachytherapy [7,8], total skin electron therapy [9,10], electron therapy [11,12], skin dose measurements [13,14], total body irradiation [15], lung and breast phantom measurements [16,17], and dose verification during cell irradiation in radiobiological experiments [18]. Through the years, RCFs produced by International Specialty Products (now Ashland, Bridgewater, NJ, USA) and released on the market under the name of Gafchromic™ models have experienced a continuous evolution, with progressive changes involving mainly the thickness of the active layer, and consequently optical properties, sensitivity and dose operating range. In particular, the EBT (External Beam Therapy) Gafchromic™ film has been recognized by the scientific community as a two-dimensional reference detector, mainly in the medical physics field [1,19]. In 2009, the EBT was replaced by the EBT2

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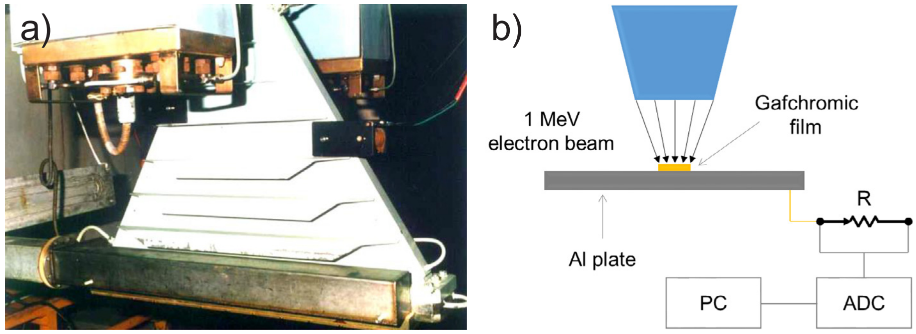

Fig. 1. (a) A picture of the head of the ILU6 accelerator at Warsaw. It provides 20 kW, few MeV electron beams. (b) Schematic of the experimental setup employed for dose measurement at ILU6.

model, characterized by a yellow marker dye in the active layer and a synthetic polymer as the binder component, whose purpose was to improve the homogeneity and reduce energy dependence [19–23]. Two years later, the new EBT3 Gafchromic™ film was made available [24]. The new model, having the same composition of the sensitive layer as well as nominal layer thickness of the EBT2, features a symmetric layer configuration which allows to eliminate side orientation dependence affecting its predecessor [23,25–28]. The potential of EBT3 has led to numerous studies aimed at analyzing the response of the new film to X-ray photon, electron and proton beams at several energies [25–34] or in specific clinical applications, like Intensity Modulated Radiation Therapy (IMRT) quality assurance measurement [23] or dose distribution measurements in stereotactic radiotherapy [35]. Another study involved the characterization of EBT3 film for ultraviolet radiation [36]. As stated by the manufacturer, EBT3 is specifically designed to obtain best performance for the applications where the maximum dose is less than 10 Gy, such as IMRT, Volumetric Arc Therapy (VMAT) and brachytherapy [24]. Indeed, there are certain clinical applications, like Bragg peak dose distribution measurements or two dimensional brachytherapy dose distribution measurements, which may require dose ranges well above those met in IMRT applications [37]. Moreover, the high dose associated to single or low-fraction applications, including Stereotactic RadioSurgery (SRS) and Stereotactic Body RadioTherapy (SBRT) increases the dose uncertainty and the impact of the lateral response artifact (LRA) for wide exposure fields [38,39]. Aiming to cover wider dose ranges, the manufacturer released different models characterized by lower dose sensitivity obtained through the use of a thinner active layer and/or a different chemical composition, like the EBT-XD, the MD-V3 and the HD-V2 [2]. An alternative approach is represented by the use of a three-channel scanner, which allows to increase the maximum measurable dose, in particular by taking advantage of the lower sensitivity of the green and blue channels, capable of delaying the saturation point with respect to the red one [19,23,26,37]. Focusing on the results recently reported for EBT3 film for high doses, a resolution lower than 3.5% was obtained for doses ranging from 1 Gy up to 120 Gy, by choosing the green or blue channel according to their respective optimal range of use [26].

A further possibility, alternative to the use of flatbed scanners, is to employ a broadband light source, which in principle could provide an accurate knowledge of the film absorption spectrum and its dependence on the dose, useful for designing a dosimeter with optimal performance [40–42]. In this work, the attention was focused on a deep analysis of the spectral response of the EBT3 film aimed at extending the measuring range to high doses up to 100 Gy while ensuring a low dose uncertainty suitable for specific applications. The present study is organized as follows: firstly, the structure of the EBT3 Gafchromic™ film is described; secondarily, the procedure of irradiation of some pieces of EBT3 film involving two types of radiations (electrons and X-rays) is shown; then, the optoelectronic setup and procedure used to measure the spectral response of EBT3 film are reported; finally, the results arising from the analysis of the acquired signals are discussed.

2. Materials and methods

2.1. Characteristics of EBT3 Gafchromic™ film

The EBT3 Gafchromic™ film is composed of a central active layer, nominally ~28 μm thick, placed between two transparent polyester substrates having a thickness of ~125 μm. The active layer contains the active component, marker dye, stabilizers, and other additives giving the film its low energy-dependent response [24]. The yellow marker dye plays two main roles: the former is to correct for subtle differences in the thickness of the active layer [1,19]; the latter is to protect the active layer from exposure to ultraviolet and ambient light [23]. The symmetric structure allows to easily manage the film without the need for keeping track of which side of the film was exposed to the light during the measurements. The dynamic dose range specified by the manufacturer is 0.1–20 Gy, while the optimal range is declared to be 0.2–10 Gy [24].

2.2. Irradiation procedures

In order to evaluate the spectral response of EBT3 Gafchromic films to dose, several pieces of film were exposed to two radiation types. In particular, a 1 MeV electron beam from ILU6 Linac Accelerator (Warsaw, Poland) and a 250 kV X-ray tube from the University of Naples "Federico II" (Italy) were used. In the following, the main steps of the irradiation procedure are discussed. Before the irradiation, a sheet of the EBT3 Gafchromic film was cut into rectangular pieces of about 20 × 7 mm^2 in order to allow the insertion of the film in the reading system. The ILU6 Linac Accelerator provides stable 20 kW, few MeV energy electron beams (Fig. 1a). The irradiations were performed by extracting the beam in air. The beam was scanned by electrodes providing a uniform (< 1%) rectangular field of 8 × 30 cm on target position (i.e. the position of the film). The pieces of film were placed on the surface of an aluminum (Al) plate positioned at a fixed distance from the output window of the accelerator. The dose in the film position is proportional both to the charge delivered on the Al plate and to the incident 1 MeV energy electron beam. The scheme of the elements used for the dose calculation is reported in Fig. 1b: i) the electron beam generates an electrical current flowing into the resistor; ii) an ADC is used to measure the voltage difference across the resistor; iii) the integral of the time measurement gives the value of the dose in the film position. Following the above mentioned procedure, six EBT3 films were exposed to electron beams for doses of 2.76, 5.52, 7.47, 11.04, 16.56 and 21.85 Gy, respectively.

The X-ray tube available at the University of Naples "Federico II" was used with 250 kVp, 15 mA and 1 mm-Cu filter. The X-ray tube was equipped with a system of adjustable collimators and a 10 × 10 cm^2 field size on the film position was used. The pieces of film were placed

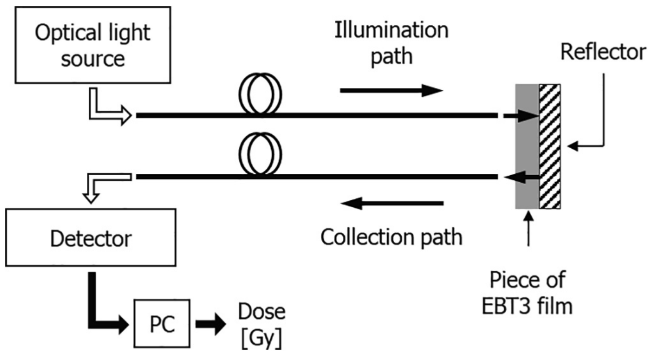

Fig. 2. A schematic of the optoelectronic setup adopted to perform the measurement of the dose in EBT3 film.

at a fixed distance from the anode position. Five pieces of EBT3 film were exposed to X-rays for doses of 0.5, 1.8, 2.2, 80 and 100 Gy, respectively. As far as dose measurements with the X-ray tube, the dose in the film position was measured by means of General Purpose Radcal Ionization Chamber (6 cm^3 active volume). More details about the dose evaluation for X-rays and electrons are reported in Ref. [43]. The films employed for the measurements reported in the present work were previously calibrated with standard flatbed scanner RCF dosimetry [43].

2.3. Optoelectronic instrumentation

A schematic of the optoelectronic setup adopted to perform the measurement of the spectral response of EBT3 films is shown in Fig. 2. It basically consisted in a fiber optic probe equipped with a couple of fiber bundles and a reflector placed at the probe end which enables the reflection mode operation, a piece of EBT3 film, a broadband light source and a spectrometer able to collect the optical signal modified by the film, and a computer to analyze data. The light source produces an optical signal travelling along the illumination path until it reaches the probe end, where a piece of EBT3 film is inserted. After passing the film, the optical signal is backscattered by a reflector, then it crosses back the film, and finally is collected by the spectrometer through a collection path.

The fiber optic probe, purchased from Avantes (Apeldoorn, The Netherlands), is shown in Fig. 3a. It features six lighting fibers with a core of 200 μm in diameter around a read fiber with the same core diameter placed in the center of the illumination fiber bundle to provide the best collection efficiency, which couples the signal back to the spectrometer. Both the illumination bundle and the read fiber are housed in flexible stainless steel jacketing. At the mid-point of the assembly, a ferrule is used to split the fibers into their respective legs (illumination or read). A white diffuser material, whose distance from the probe termination is adjustable by means of a thread, plays the role of reflector (Fig. 3b).

The light source AvaLight-DH-S-BAL Balanced Power, purchased from Avantes, was set to work in the wavelength range 500–2500 nm, covering the spectral interval where the changes in the optical properties of EBT3 film are expected [2], avoiding any alteration of the film response induced by lower wavelengths [36]. Finally, the spectrometer AvaSpec-ULS2048XL, purchased from Avantes, was set to acquire the spectral interval 200–1160 nm and was controlled via computer by using the AvaSoft 8.1.5 software.

2.4. Read-out procedure

It is well known that RCFs are able to change their absorption properties when exposed to ionizing radiations, reducing their capability to transmit the visible light. In principle, any device capable of detecting changes in the transmitted or reflected light can be adopted to read the dose absorbed by a RCF. However, any variation in the instrumentation, either in the film model or in the measurement procedure, leads to a different dose response calibration curve [1]. Over the years, several instrumentations have been used for film dosimetry [44], but flatbed document scanners are the most widely employed [2]. Referring to dosimetry systems based on EBT3 film, the versatility of the flatbed scanner has been recently investigated in terms of the optimal response function originating from the film images obtained in both transmission and reflection scanning mode [33]. Moreover, the same authors made an assessment of the necessity of scanning film pieces before and after irradiation, concluding that a single scanning approach can be considered sufficient for most of clinical and research applications. Another recent study on EBT3 films reported an innovative multistage model involving the use of the Monte-Carlo analysis providing a complete characterization of the uncertainties in RCF dosimetry with single-channel and multichannel algorithms [34]. The influence of the reading device model in the final uncertainty of the dose estimates with single-channel and multichannel algorithms was also assessed. In this work, an optical setup involving a broadband light source and a spectrometer has been used to analyze the changes in the optical properties of the EBT3 film after exposure to ionizing radiations [37,40–42,45,46]. Since the exposure to radiations reduces the transmittance of the film,

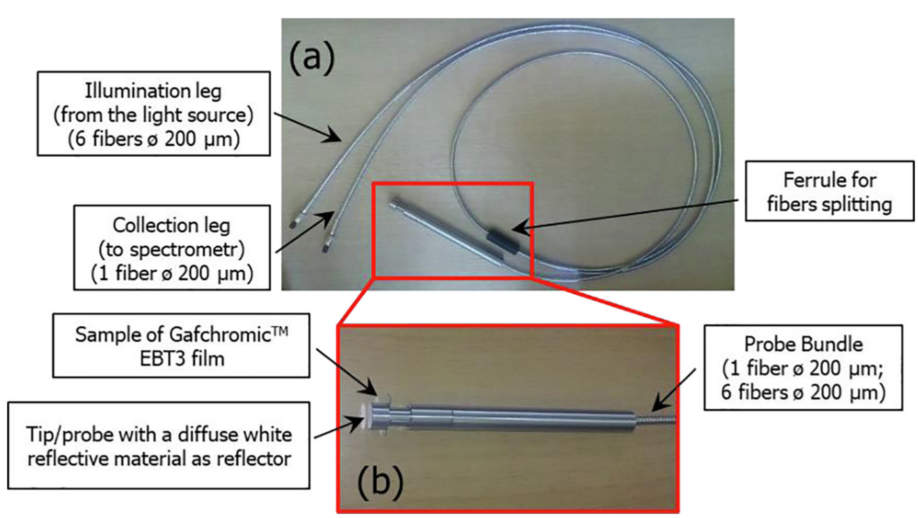

Fig. 3. (a) The fiber optic probe used to measure changes in the optical properties of an EBT3 Gafchromic™ film. (b) In the bottom, a particular of the probe end, hosting a piece of an EBT3 film.

the first measurement was carried out on an unexposed piece of EBT3 film in order to set the maximum integration time allowing a full acquisition of the spectrum in the range 500–1160 nm without incurring the saturation of the spectrometer. This approach allows to explore all the existing spectral features and, consequently, to choose one or more observables able to discriminate the low or high doses. Afterward, the spectra of the eleven samples previously irradiated with electrons or X-rays in the range 0.5–100 Gy were acquired. For each sample, five acquisitions were executed, in order to perform a statistical analysis of the collected data. After each acquisition, the sample was removed and then re-inserted within the fiber optic probe cover, in order to expose different sample areas to the reading of the probe, keeping into account the possible inhomogeneity of the film and, at the same time, the error made in fixing operations. Each spectrum was subtracted from the dark signal acquired by the spectrometer when the light source was switched off.

3. Results and discussion

3.1. EBT3 spectral response

The average spectra upon five measurements concerning the EBT3 samples exposed to 1 MeV electron beam and to the 250 kV X-ray tube are reported in Fig. 4 in terms of intensity, expressed in Counts, against the wavelength for different doses indicated by the legend. The average spectrum related to the unexposed sample (0 Gy) is also reported.

As the absorbed dose increases, the intensity of the acquired signal decreases in the visible spectrum as a consequence of the progressive darkening of the film. This decrease is also observable for higher wavelengths, but starting from 700 nm there is no monotonous behavior for all the doses taken into consideration. In principle, the integration time could be increased in order to amplify the acquired signal in the approximate range 500–650 nm, where the film response to the dose is monotonous. However, doing so, the right side of the spectrum, being more intense, saturates becoming unusable, thus losing information from that interval. Moreover, given the flattening of the spectrum for high doses in the range 500–650 nm, it is to be expected that any increase in integration time would be limited to increase both the dark signal and the less intense signals equally, without any advantage in terms of signal-to-noise ratio for high doses.

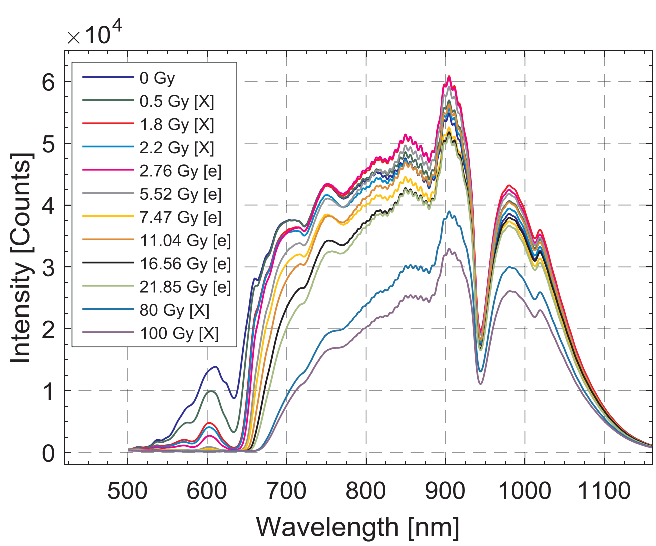

Fig. 4. Average intensity spectra obtained upon five acquisitions from EBT3 film samples exposed to 1 MeV electron beam (referred as [e] in the legend) and to the 250 kV X-ray tube (referred as [X]). The spectrum of an unexposed sample is also shown.

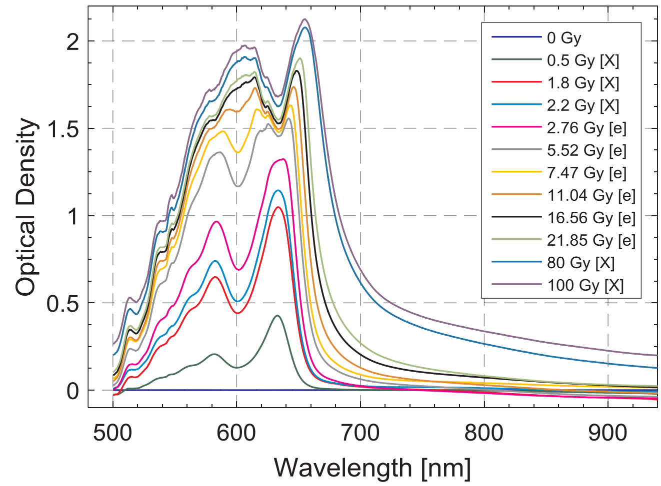

Fig. 5. Average OD spectra obtained upon five acquisitions from EBT3 film samples exposed to 1 MeV electron beam (referred as [e] in the legend) and to the 250 kV X-ray tube (referred as [X]). The null OD of the unexposed sample used as reference is also shown.

3.2. Optical density

The signal acquired by the spectrometer contains the transfer functions of each component in the measurement setup (light source, lighting fibers, film, collecting fiber and spectrometer). For this reason, the response of a RCF, commonly reported as optical density (OD), is generally normalized to that of the unexposed film, so as to highlight the changes undergone by exposure to radiation [1,47]. In this work, we refer to the net OD, defined as follows:

$$OD(\lambda) = \log_{10}[I_0(\lambda)/I(\lambda)] \tag{1}$$

where $I_0(\lambda)$ is the intensity of the signal acquired from an unexposed sample (with a dose of 0 Gy), and $I(\lambda)$ is the intensity of a generic sample. Both the intensities adopted to calculate the OD are subtracted from the dark signal saved when the light source is switched off. The average OD spectra calculated from the acquired signals are reported in Fig. 5.

According to the formula, the OD spectrum related to the unexposed sample is null, since it is used as reference. For the exposed samples, the OD increased with the dose absorbed by the film; in particular, the highest values are achieved in the interval 500–700 nm, where two peaks are visible for doses as low as ~2 Gy, approximately at 582 and 633 nm, respectively. This shape is consistent with previous literature [2,24,40]. Further increasing the dose, the shape of the OD changes, losing these characteristic spectral features. It has been observed that a change in the shape of the peak of OD at higher doses can be explained by the limited sensitivity of the spectrometer combined with the small amount of light crossing the darkened film [41]. While usually this phenomenon results in a flattening of the peak, in our case there is a sort of splitting of the main peak. In order to evaluate the variations induced by the dose in the OD spectrum, different spectral features could be taken into account. One of these consists in considering the OD at a precise wavelength, or its average value or the integral in a particular spectral range, including one or more peaks [6,20,45,48]. In this work, the OD calculated at the two main peaks exhibited for low doses (581.5 and 633.2 nm, respectively) was reported as a function of the dose (Fig. 6a and b). Some studies carried out in recent years have shown that the EBT3 film guarantees a low dependency of the response from the type and energy of radiation [25,30]. This is true for low Linear Energy Transfer (LET) radiation such as those employed in this work. In particular, a unique calibration curve matching the response of 70 EBT3 film samples exposed to different radiation fields, including those used in the present work, achieving a deviation from the

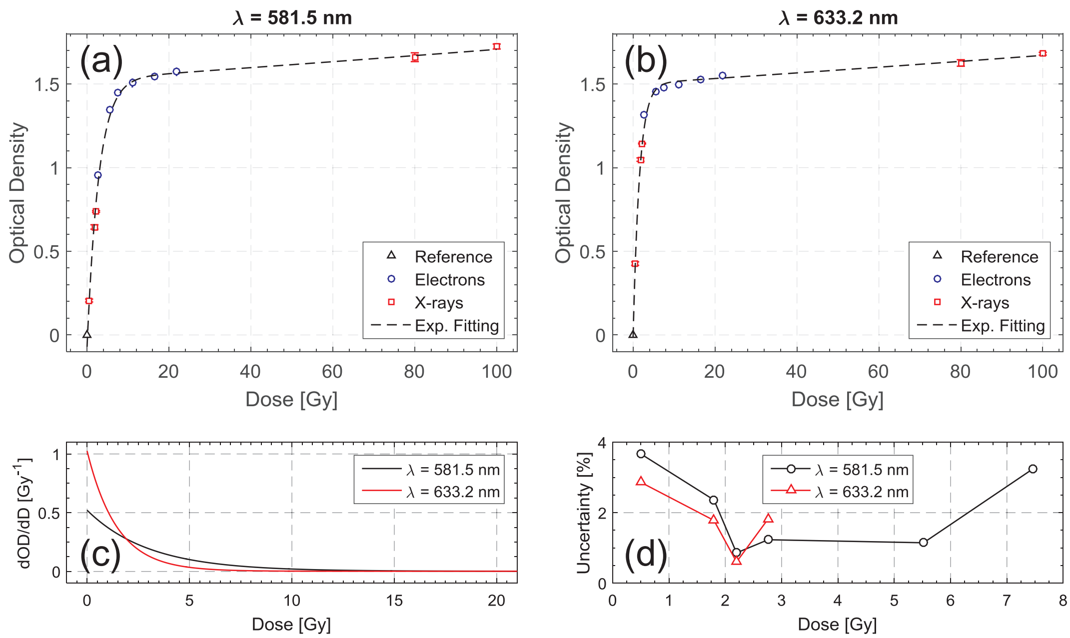

Fig. 6. (a and b) Experimental data and calibration curves reporting the OD at the peak wavelengths 581.5 (a) and 633.2 nm (b) as a function of the dose absorbed by EBT3 film samples; different markers and colors are used according to the type of radiation; the dashed lines refer to the fitting functions; error bars refer to the standard deviation upon five measurements for each sample. (c) Sensitivity curves reporting the first derivative of the two calibration curves. (d) Experimental uncertainty for low doses, limited to points under 4%.

experimental values of only a few percentage points, has been reported in Ref. [43]. Based on these results, EBT3 film samples exposed to both 1 MeV electron beam and 250 kV X-rays were grouped together to identify a single calibration curve. To fit experimental data, an exponential fitting was used (D = dose):

$$f(D) = a \cdot \exp(b \cdot D) + c \cdot \exp(d \cdot D) \quad (2)$$

The coefficients of the fitting functions (a, b, c, d) were obtained using the Curve Fitting Toolbox™ available in MATLAB® environment. The R-square ranged between 0.9959 and 0.9979.

In order to better analyze the calibration curves, a sensitivity curve displaying the first derivative of the OD versus the dose was obtained (Fig. 6c). This graph shows unequivocally how the sensitivity of the OD at the selected wavelengths rapidly tends to saturation for doses higher than 10 Gy.

In order to evaluate the performance of the proposed approach, the dose (one-sigma) uncertainty (σ_D) was calculated from the standard deviation of the OD at selected wavelengths (σ_{OD}) arising from five measurements performed in different points of each sample in order to take into account also the inhomogeneity of the film and the error made in fixing operations. The σ_{OD} was divided by the sensitivity (i.e. the first derivative of the OD vs the dose) dOD/dD, adopting the same equation reported here [26]:

$$\sigma_D = \sigma_{OD}/(\mathrm{d}OD/\mathrm{d}D) \quad (3)$$

This quantity does not consider the uncertainty originating from the fitting of the calibration curve, which should be combined with the experimental uncertainty [44]. Actually, the low sensitivity at high doses leads to an increased dose uncertainty, as reported by the manufacturer [24]. However, if the measuring range is restricted to the interval 0.5–7.47 Gy and the secondary peak at 581.5 nm (not affected by the deformation of the main peak due to the limited sensitivity of the spectrometer) is considered, it is possible to keep the dose uncertainty below 4% (Fig. 6d). These values are substantially in line with those recently obtained in the same dose range with a three-channel flatbed scanner [26].

3.3. Innovative wavelength-based data analysis technique for dose calibration

To outperform the above-mentioned classical approaches, especially when high doses are considered, the OD spectrum was further analyzed. The main limitation of the approaches based on the measurement of the OD in a defined range or at fixed wavelength is the unavoidable saturation of the main peak around 635 nm. This saturation appears as a distortion of the main peak and densification of the spectra as the dose increases, and it depends on the dynamic range of the optoelectronic instrumentation employed [41]. Nevertheless, as the dose increases and consequently the main peak starts to saturate, the OD continues to increase in correspondence of the wavelengths that are far from the nominal EBT3 absorption peaks [42]. This principle is also the basis of the three-channel flatbed scanner dosimetry [19,23,26,37]. In this paragraph, we discuss an innovative wavelength-based approach for dose calibration as an alternative to the standard measurements based on the evaluation of OD at fixed wavelength. The proposed method consists in the evaluation of the wavelength position of the decreasing edge of the OD spectrum on the right of the main peak at a fixed OD level (Fig. 5). The possibility of choosing different OD levels allows the exclusion of parts of the spectrum affected by saturation. The calibration curve, sensitivity and uncertainty evaluated by selecting different OD levels are reported in Fig. 7. In particular, here we presented the results obtained when the OD = 0.5, covering the range 1.8–100 Gy (Fig. 7a). The calibration fitting function was found to be the same for film samples exposed to X-rays and electrons, as discussed in paragraph 3.2. Large variations of the wavelength position of the OD spectrum in correspondence of a fixed OD level of 0.5 with sensitivities of 2.5 nm/Gy for low doses down to 0.6 nm/Gy for high doses over 40 Gy were observed (Fig. 7c). The proposed approach enables the extension of the dynamic range of the film (2.2–100 Gy) with an uncertainty below 5% (Fig. 7d).

In order to improve the overall performance in terms of uncertainty, we can act on the selection of the optimum OD value. In particular, a cut at OD = 1.25 provides a reduction of the measuring dose range (2.76–100 Gy) (Fig. 7c) with sensitivities of 2.2 nm/Gy for low doses down to 0.2 nm/Gy for higher doses (Fig. 7c). Nevertheless, the portion

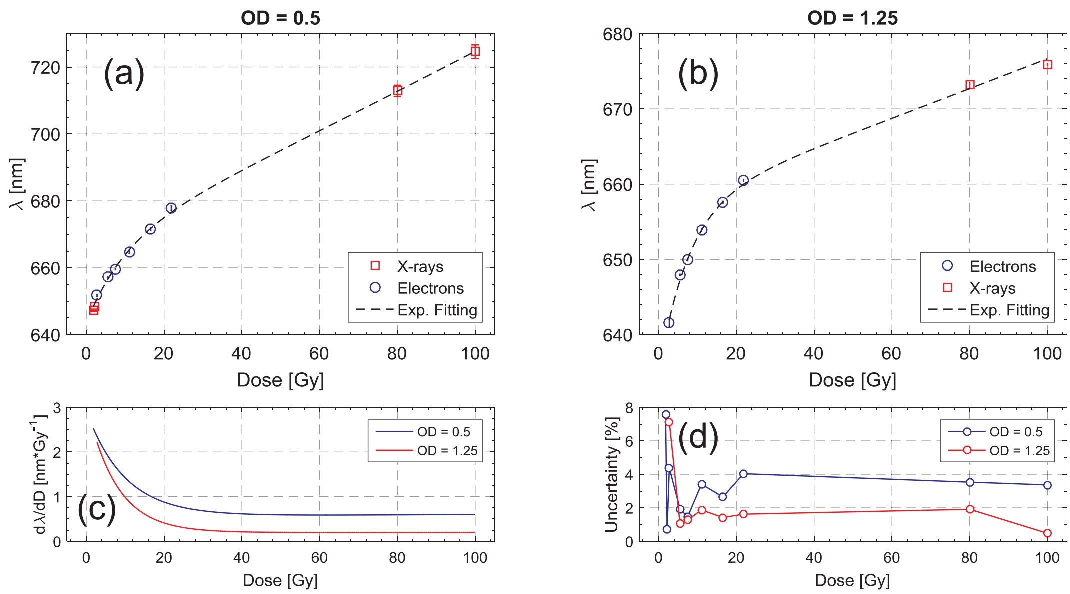

Fig. 7. (a and b) Experimental data and calibration curves reporting the wavelength evolution of the OD spectrum at a fixed OD of 0.5 (a) and 1.25 (b) as a function of the dose absorbed by EBT3 film samples; different markers and colors are used according to the type of radiation; the dashed lines refer to the fitting functions; error bars refer to the standard deviation upon five measurements for each sample. (c) Sensitivity curves reporting the first derivative of the calibration curves. (d) Experimental uncertainty calculated as shown in Eq. (3), but referred to the wavelength at a fixed OD level in place of OD.

of the spectrum analyzed by this method, ranging from about 640–676 nm, guarantees a much lower standard deviation, allowing to lower the uncertainty below 2% (Fig. 7d). As matter of fact, it would be possible to select different OD levels in order to adapt the measurable dose range as well as the related uncertainty for the specific application. As general rule, by lowering the OD level, larger measuring ranges are achievable with a lower precision, while an increase in the OD level may be useful in terms of reducing uncertainty if the measure is confined to high dose ranges.

3.4. Fitting procedure and dose uncertainty analysis

Combining the results obtained by using the two techniques discussed above, it is possible with a single spectral acquisition to cover the full dose interval investigated ranging from 0.5 to 100 Gy with an experimental uncertainty lower than 4%, which decreases below 2% when absorbed doses higher than 5.52 Gy are considered. These results improve those recently reported for the same film model in Ref. [26], where a dose resolution lower than 3.5% was guaranteed in the 1–120 Gy range, by choosing the green or blue channel according to their respective optimal range of use.

In order to show concretely the advantage arising from the integration of the different spectral features analyzed in the previous sections, we developed a dynamic fitting procedure in which the OD corresponding to a certain wavelength or the wavelength corresponding to a fixed OD level were selected in the respective optimal dose ranges. Similar approaches applied to EBT3 film can be found here [26,30]. Through this technique, doses between 0 and 100 Gy were analyzed using three different fitting functions (of the same type as the one shown in equation (2)) defined in limited dose ranges in order to minimize the total dose uncertainty (Fig. 8).

The total dose uncertainty was calculated according to the formula:

$$\sigma_{tot} = (\sigma_{exp}^2 + \sigma_{fit}^2)^{1/2} \quad (4)$$

where σ_{exp} is the experimental dose error, σ_{fit} is the dose error generated by the fitting, and σ_{tot} is the resulting total dose uncertainty. Both σ_{exp} and σ_{fit} were calculated using Eq. (3), starting from the experimental standard deviation and the fitting error, respectively.

Regarding low doses, OD at 633.2 nm was chosen, given the well-known sensitivity of EBT3 film in this region of the spectrum. Using a fitting function limited to the range 0–21.85 Gy, a total uncertainty lower than 4% was obtained in the range 0.5–2.2 Gy (Fig. 8b). It is important to point out that these doses could not be evaluated through the wavelength-based approach, or they were but with high experimental uncertainties, as shown in Fig. 7d. As regards the subsequent range of doses, the wavelength at OD = 0.5 was preferred, since if the fitting function is restricted to the range 2.2–16.56 Gy, a total dose uncertainty below 3% can be obtained in the range 2.2–5.52 Gy, which is better than the performance achieved by the other functions considered. For the remaining interval 5.52–100 Gy, the fitting function of

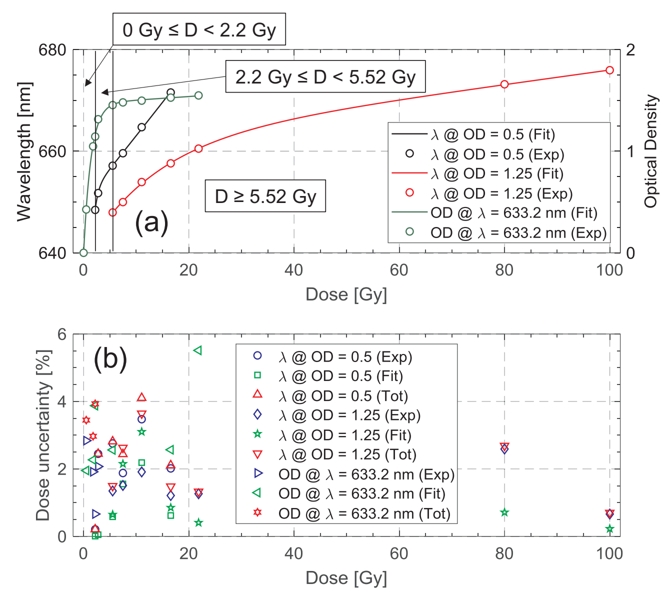

Fig. 8. (a) Experimental data and fitting functions of both the OD corresponding to a certain wavelength and the wavelength corresponding to a fixed OD level, as a function of the dose absorbed by EBT3 film samples; vertical black lines indicate bounds of the dynamic ranges adopted to optimize the performance of each fitting function; (b) Dose uncertainty corresponding to the above-reported experimental data and fitting functions.

the wavelength corresponding to OD = 1.25 limiting the total uncertainty below 4%, was used. The overall result of this analysis is the demonstration of the possibility of measuring doses in the range 0.5–100 Gy through different quantities coming from a single spectral acquisition, obtaining a total dose uncertainty lower than 4% (and better in some sub-intervals) improving the performance reported so far with EBT3 film for comparable dose range [26]. It should be noted that an appropriate selection of optoelectronic instrumentation could reduce the impact of experimental uncertainty. The fitting procedure, in turn, can be further refined through a denser sampling of the dose in the region of interest and by means of dedicated numerical methods.

4. Conclusions

A new read-out method to improve the performance of EBT3 Gafchromic films at high dose levels has been proposed and successfully demonstrated. An optical setup involving a broadband light source, a fiber optic probe working in reflection configuration and a spectrometer has been used to detect changes in the spectral response of several EBT3 films exposed to 1 MeV electrons and 250 kV X-rays for doses ranging from 0.5 to 100 Gy. The experimental results reported here have shown that a broadband instrumentation provides a remarkable variety of spectral features tightly correlated to the dose absorbed by the EBT3 film. Among these, the common approach to consider the OD evolution pertaining to specific wavelengths allowed to distinguish doses in the range 0.5–7.47 Gy with experimental uncertainty below 4%. The analysis of the entire OD spectrum also reveals a significant change in the falling edge located at the right of the main OD peak as the absorbed dose increases. The monitoring of the position of this spectral feature at a fixed OD value led to a significant extension of the dose range up to 2.2–100 Gy with experimental uncertainties below 5%. By acting on the OD value as degree of freedom for performance tuning, uncertainties lower than 2% in the range 5.52–100 Gy have been obtained. Finally, through a dynamic fitting procedure integrating both the OD and the wavelength-based approaches, a total uncertainty lower than 4%, including the experimental and fitting errors, was demonstrated in the whole range 0.5–100 Gy. It is worth noting that performance here achieved in terms of both sensitivity and uncertainty may be further improved through an optimization of the optoelectronic instrumentation adopted and of the positioning mechanism of the film sample in the readout system. When compared with standard techniques such as flatbed scanners, the dosimetric methodology proposed here has the advantage of providing higher sensitivity with low uncertainty at higher doses through a wavelength-based analysis of the spectral features of a radiochromic film. Moreover, the size of the film required for dose measurement is significantly reduced compared to that needed by flatbed scanners due to use of optical fibers as reading tool. Furthermore, if the reflector is made of materials such that the interaction of ionizing radiation with the reflector is negligible and, at the same time, it is reflective for VIS/NIR light, the proposed method can be easily translated to application scenarios that require real-time measurements of the dose absorbed by RCFs [49]. Actually, flatbed scanner dosimetry allows integral measurements of dose of larger regions usually needed in applications such as beam centering and beam visualization. The practical use of the method proposed here is addressed to dosimetry application only and not to profile measurements. However, a motorized stage can be designed to overcome this limitation.

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