Radiochromic EBT2 and EBT3 sensitometry based on growth of two color phases of the polymer

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Purpose: The aim of this work is to develop a sensitometry model of EBT2 and EBT3 radiochromic films based on the observation that radiation induces growth of two polymer color phases.
Methods: Previously published data of the active layer absorption spectrum have been used to characterize the contribution to the total absorbance of each polymer color phase. Through a prior proposed external beam therapy absorption spectrum model the total absorbance has been deconvolved into two polymer phase contributions. The integral absorbance in the visible spectrum of each color phase has been calculated and parametrized as an absorbed dose function. A sensitometry model employing linear relationships with the color phase integral absorbances has been investigated. The phase linear coefficient ratio for each color channel is proposed to be a constant. Films belonging to six different production batches, three EBT2 and three EBT3, have been used to verify this model.
Results: Each polymer color phase integral absorbance in the visible spectrum has been expressed as a simple saturation function of the absorbed dose to the film. The data coming from the six production batches have been fitted to the proposed sensitometry model. This model predicts the measured dose variation in the active layer light attenuation up to fluctuations attributable to uncertainties.
Conclusions: The calibration curve can be written as a linear combination of simple functions describing the dose dependence of the integral absorbance of each polymer color phase. These functions are characteristics of the active layer material, and not dependent on the model and production batch. According to the proposed model, to calibrate a batch in terms of the active layer light attenuation consists of determining just one linear coefficient. [https://doi.org/10.1002/mp.13424]

Key words: film dosimetry, Gafchromic EBT2 and EBT3, radiochromic film, sensitometry

1. INTRODUCTION

Radiochromic films present some advantages over other 2D radiation detectors. Due to their composition based on light elements they have low-energy dependence and near biological tissue equivalence, in addition to the high spatial resolution that characterizes film dosimetry.[1] Until the introduction of the Gafchromic™ external beam therapy (EBT) their main disadvantage was low sensitivity. However, the EBT model and its evolutions, EBT2 and EBT3, have a suitable range for the radiotherapy typical dose.[2,3]

A film dosimetry system consists of the film and the reader. It is common practice to use a flatbed scanner for reading out the film.[4,5] This kind of device often uses a cold cathode fluorescent lamp as light source, an optical system to split the light into three color channels, and a linear CCD array as the imaging sensor. In order to measure absorbed dose a curve relating reader digital signal and film dose is required.

A wide variety of functional forms of this curve have been proposed.[6,7] Del Moral et al.[8] and more recently Martin Viera et al.[9] have developed models on the light passing through the medium based on the percolation theory.

Rink,[10] while developing a real-time *in vivo* dosimetry system with the EBT film as a sensor, proposed to describe the light absorption in the film as a function of the absorption center density and the absorption spectrum of these centers. Rink also suggested that two types of absorbers were developing in the film.

Several authors have independently published absorbance measurements of the EBT models. Butson et al.[11] analyzed the EBT sensitivity differences compared with previous HS radiochromic films. Devic et al.[12] established that the active layer for the EBT model has two main absorbance peaks with six other minor peaks, and that the wavelength of the maximum of the peaks does not change with dose. After the EBT2 release, Butson et al.[13] measured the change in absorption spectra properties and in sensitivity from EBT to EBT2 models, and Devic et al.,[14] concluded that both models presented the same dosimetric properties. Callens et al.[15] performed visible and Raman spectroscopy to investigate the

molecular nature of the radiochromic properties of EBT3 films, confirming the presence of two polymer conformations and elaborated a model to deconvolve the absorption peaks that the EBT3 active layer presents.

Here, we analyze the absorbance measurements published by Butson et al.[13] using the model proposed by Callens et al.[15] to characterize the integral absorbance in the visible spectrum of each polymer color phase as a dose function. Using these results we introduce a new model that relates dose with scanner digital signal for EBT2 and EBT3 models.

2. METHODS

2.A. Active layer absorption in the visible spectrum of EBT film models

Following Callens et al.[15], the absorbed dose to the active layer of EBT film models induces a polymerization reaction joining diacetylene monomers. The formed polymers can grow in three different configurations, the so-called red, blue, and bluish-green phases. Callens' measurements indicate that the bluish-green phase is not detectable. In the visible spectrum each polymer phase with a given conjugation length presents an absorption peak corresponding to the electronic transition from the ground level to the excited state and other absorption peaks corresponding to transitions to vibrational levels of the electronic excited state. The absorption spectrum can be modeled by

$$OD(\bar{\nu}) = \sum_p \sum_n f(n) \left(\frac{E_p \Gamma_{p,e}}{(\bar{\nu} - \bar{\nu}_{p,e})^2 + \Gamma_{p,e}^2} + K_p \sum_k \frac{a_{p,k} \Gamma_{p,v}}{(\bar{\nu} - \bar{\nu}_{p,k})^2 + \Gamma_{p,v}^2} \right), \quad (1)$$

where $\bar{\nu} = 1/\lambda$ with λ denoting light wavelength, p represents each polymer color phase, n the conjugation length, E_p and K_p the electronic and vibronic transition intensities, $\Gamma_{p,e}$ and $\Gamma_{p,v}$ the electronic and vibronic peak absorption widths, $\bar{\nu}_{p,e}$ and $\bar{\nu}_{p,k}$ the central frequency of each absorption peak for electronic and vibrational transitions, respectively, and $a_{p,k}$ the vibronic transition relative intensities. $\bar{\nu}_{p,e}$ is determined by the polymer color phase and the conjugation length and $\bar{\nu}_{p,k}$ by the same parameters and the Raman shift for the k vibronic transition. The relative intensities $a_{p,k}$ can be determined as well by Raman spectroscopy. The parameters $\bar{\nu}_{p,e}$ and $a_{p,k}$ have been measured by Callens et al.[15]

$f(n)$ is the relative frequency of the polymer conjugation length n and it can be described, according to Callens et al. by means of a log-normal distribution

$$f(n) = \frac{1}{\sqrt{\pi} n \delta} e^{\frac{-ln^2(n/n_0)}{\delta^2}}, \quad (2)$$

where n_0 represents the more frequent conjugation length and δ the distribution width.

Equation (1) allows us to calculate the integral absorbance of each polymer color phase

$$IA_p = \sum_n f(n) \int_{\bar{\nu}_{min}}^{\bar{\nu}_{max}} \left(\frac{E_p \Gamma_{p,e}}{(\bar{\nu} - \bar{\nu}_{p,e})^2 + \Gamma_{p,e}^2} + K_p \sum_k \frac{a_{p,k} \Gamma_{p,v}}{(\bar{\nu} - \bar{\nu}_{p,k})^2 + \Gamma_{p,v}^2} \right) d\bar{\nu}, \quad (3)$$

where $\bar{\nu}_{min} = 1/700$ nm^{-1} and $\bar{\nu}_{max} = 1/400$ nm^{-1} for the visible spectrum.

2.B. Integral absorbance dependency with absorbed dose

The active layer absorption spectrum of the EBT films has been analyzed by several authors. Butson et al.[13] measured EBT2 absorption spectra in a dose range between 0.25 and 5 Gy using a 6-MV beam, to identify sensitivity changes between EBT and EBT2 models. A 5-nm wavelength step was used. Their measurements were published in a graphic chart with a marker in every measurement. To recover the absorbance measured by them we have digitalized the chart locating every marker.

Butson et al.'s measurements have been fitted to Eq. (1) in the dose range from 0.5 to 5 Gy. The 0.25 Gy measurements were not taken into account because they barely stand out from the signal background. As several parameters in Eq. (1) have been previously determined,[15] to fit absorption in the visible spectrum measurements we have 10 parameters left: the most likely conjugation length n_0 and the width δ in the distribution f, and the intensities E_p, K_p and the absorption peak widths $\Gamma_{p,e}$, $\Gamma_{p,v}$ for each polymer color phase. These parameters have been determined using a nonlinear least squares method.

We have employed Eq. (3) to separate total integral absorbance into contributions due to the red and blue color phases. Total integral absorbance is proportional to the polymer number growth caused by absorbed dose. The rate of this growth with dose must decrease as the number of available monomers to form new polymers diminishes. We have parametrized each polymer color phase contribution by

$$IA_p(D) = IA_{p,s} + \left(IA_{p,0} - IA_{p,s}\right) e^{-k_p D}, \quad (4)$$

where $IA_{p,0}$ and $IA_{p,s}$ are the integral absorbance for the p polymer color phase when the film has not been irradiated and when it is saturated, that is, when no more monomers are available to initiate a polymerization reaction. k_p is proportional to the incremental variation in IA_p with dose.

2.C. Sensitometry of EBT film models

In this work, we want to relate the absorbed dose to a film with the change in color produced. The change is characterized by the light absorption in the film, measured by a flatbed scanner in transmission mode. The scanner reads the intensity and color of the light that passes through the film and produces an image of pixels, each one with an RGB digital signal.

If the light emitted by the scanner lamp has an intensity $I_0(\lambda)$, the transmitted light intensity I_T through the film with absorption spectrum $OD(\lambda)$ as measured in a color channel with response function $R(\lambda)$ can be expressed as

$$I_T = \int I_0(\lambda) 10^{-OD(\lambda)} R(\lambda) d\lambda. \tag{5}$$

The digital signal S the scanner produces is proportional to the relative transmitted light intensity to the light intensity with no attenuation

$$S = \frac{I_T}{I_0} 2^{16},\ I_0 = \int I_0(\lambda) R(\lambda) d\lambda, \tag{6}$$

where we are considering a bit depth of 65536 levels. Figure 1 shows the light spectrum of the cold cathode fluorescence lamp (CCFL) and the response curves of the tricolor CCD used both by the scanner. Superimposed it is shown as well the absorption spectrum of the film, including active and nonactive layers.

For practical reasons we make the variable change

$$d_G = log_{10} \frac{2^{16}}{S} = log_{10} \frac{I_0}{I_T} = log_{10} \frac{I_0}{\int I_0(\lambda) 10^{-OD(\lambda)} R(\lambda) d\lambda}, \tag{7}$$

with $OD(\lambda) = OD_N(\lambda) + OD_r(\lambda) + OD_b(\lambda)$, where $OD_N(\lambda)$, $OD_r(\lambda)$, $OD_b(\lambda)$ are the nonactive layer, red, and blue polymer phases absorption spectrum, respectively.

Using the product logarithm identity Eq. (7) can be expressed as well

$$d_G = log_{10} \frac{I_0}{\int I(\lambda) 10^{-OD_n(\lambda)} R(\lambda) d\lambda} + log_{10} \frac{\int I(\lambda) 10^{-OD_n(\lambda)} R(\lambda) d\lambda}{\int I(\lambda) 10^{-OD(\lambda)} R(\lambda) d\lambda}. \tag{8}$$

The first term of this sum is not a dose function, it depends on the optical properties of the nonactive materials used to manufacture the film. It represents the d_G value of a nonirradiated film. Subtracting it we can define

$$d(D) = log_{10} \frac{\int I(\lambda) 10^{-OD_n(\lambda)} R(\lambda) d\lambda}{\int I(\lambda) 10^{-OD_n(\lambda)} 10^{-(OD_r(D,\lambda)+OD_b(D,\lambda))} R(\lambda) d\lambda}. \tag{9}$$

$I(\lambda) 10^{-OD_n(\lambda)}$ is the light spectrum of the scanner filtered by the nonactive materials of the film, so Eq. (9) expresses that $d(D)$ is the active layer optical density as measured by the scanner, which results from a combination of two absorbers. In this work, we are going to investigate if the dose dependence of d can be approximated as a linear combination of $IA_r(D)$ and $IA_b(D)$

$$d(D) = \phi_r \cdot \left(1 - e^{-k_r D}\right) + \phi_b \cdot \left(1 - e^{-k_b D}\right), \tag{10}$$

where ϕ_r and ϕ_b are related with the abundance of each polymer color phases, and the parameters k_r and k_b are those obtained fitting the deconvolved integral absorbance spectra of each polymer phase. ϕ_r and ϕ_b should depend on the scanner lamp spectrum and the scanner color filters, besides the active layer absorption spectrum.

2.D. Calibrations

Film samples belonging to six different batches have been calibrated, meaning establishing the relation $d = d(D)$ for all color channels. Three batches belonged to EBT2 model and three batches belonged to EBT3 model.

Ten film cutoff patches, 3 cm × 3 cm in size, all from the same batch, were used in each calibration. Before being cutoff, each piece was numbered in its top right corner to track the orientation of the film. They were irradiated in the center of a 10 cm × 10 cm square field, inside a RW3 phantom 10-cm depth and 100-cm source film distance. A 6-MV beam from a Siemens Artiste linear accelerator was used. The machine is subject to a quality control program and the dose is well established and traceable. Each piece was irradiated with a uniform absorbed dose of 0.5, 0.75, 1, 1.25, 1.5, 2, 3, 4, 5 Gy and one of them was left without being irradiated.

Twenty-four hours after irradiation, the sample was scanned on a Microtek ScanMaker 1000 XL, all patches at

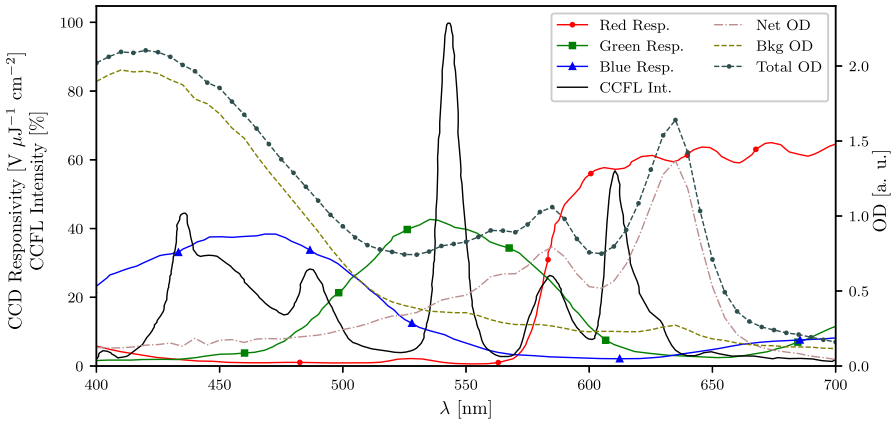

FIG. 1. CCFL spectrum, CCD responsivity, and film absorption spectrum of the elements used in this work. [Color figure can be viewed at wileyonlinelibrary.com]

the same time and keeping their orientation. We have chosen to scan in a parallel direction to the long edge of the film the pieces belong to. The sample was placed at the center of the A3 size glass window. A holder was made of two nonirradiated films for proper positioning of the pieces. Both layers of the holder have 10 square holes, each one 2.5 cm × 2.5 cm in size at the bottom layer and 3 cm × 3 cm in size at the upper layer. This setup allows us, once the calibration pieces are placed in the holder, fitted into the upper layer holes, to scan them through the ten square open windows of 2.5 cm × 2.5 cm without touching the scanner glass, minimizing the creation of Newton's rings and assuring a uniform distance to the glass plate. The scanner was switched on for several hours and its lamp was lit for at least fifteen minutes to stabilize its temperature before scanning. The scanned image was 30 dpi in spatial resolution and the digital signal was 48 bits in depth, so 16 bits were used for each color channel. Any other additional correction by the scanner was switched off. Five consecutive scans of each calibration sample were taken and the average image was analyzed.

Data from these scans were fitted to calibration curves following the Eq. (10) model. The fit has been made by means of lasso (least absolute shrinkage and selection operator), a type of regression that performs variable selection and regularization and allows us to identify if one of the color phases has a nonsignificant contribution to d. If both phases contribute to d, the relative abundance of the blue phase to the red phase can be calculated in advance. Denoting $\rho = \phi_b/\phi_r$ Eq. (10) can be written

$$d(D) = \phi_r \cdot \left[\left(1 - e^{-k_r D}\right) + \rho \cdot \left(1 - e^{-k_b D}\right)\right]. \tag{11}$$

Using two different dose values D_1 and D_2 results

$$\rho = \frac{(1 - e^{-k_r D_1})d(D_2) - (1 - e^{-krD_2})d(D_1)}{(1 - e^{-k_b D_2})d(D_1) - (1 - e^{-k_b D_1})d(D_2)}, \tag{12}$$

where $d(D)$ is calculated using Eq. (9) with $I(\lambda)$, $R(\lambda)$, $OD_n(\lambda)$ data as shown in Figure 1. Active layer OD values are taken from the measurements published by Butson et al.

According to this model, to calibrate a batch in terms of net attenuation $d(D)$, should consist of determining the value of ϕ_r for each color channel.

3. RESULTS

3.A. Integral absorbance

Figure 2 shows the spectral absorbance measurement for 2 Gy taken from Butson et al.[13] and its fit to the model proposed by Callens et al.,[15] Eq. (1). The figure shows as well the different contribution to the total absorbance of each polymer color phase. These fits have been made for every absorbance spectra measured by Butson et al. in the dose range between 0.5 and 5 Gy.

Figure 3 shows the integral absorbance for each color phase obtained using Eq. (3) applied to the absorbance spectrum fits. The color phase integral absorbances were fitted to

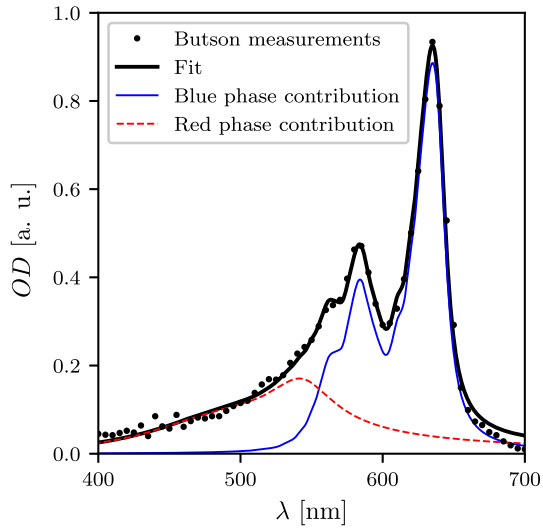

FIG. 2. Absorbance measurements taken from Butson fitted to the model proposed by Callens. The continuous and dashed thin lines are the blue and red phase contributions, respectively, to the total absorbance. [Color figure can be viewed at wileyonlinelibrary.com]

Eq. (4). The saturation rate parameters we obtained were $k_r = 0.0982 \pm 0.0008$ Gy^{-1} and $k_b = 0.261 \pm 0.003$ Gy^{-1}.

3.B. Sensitometry model and calibration measurements

Figure 4 shows the calibration measurements for six different production batches belonging to two film models, EBT2 and EBT3, and their fits to the model proposed in Eq. (10) by means of lasso regression. The variable selection of these regressions indicates that the ϕ_b parameter can be excluded from the sensitometry model for the green and blue channels. For the red channel using Eq. (12) with the Butson absorbance measurements for $D = 2$ and $D = 3$ we have calculated a relative polymer phase abundance $\rho = 1.67 \pm 0.02$. Table I presents the fit parameters, the value of χ^2 for the fit normalized by the number of degree of freedom. χ^2_n values have been calculated considering an estimated d uncertainty of ± 0.003. As another measure of goodness of fit, due to the proposed model is a linear regression model, the regression coefficient of determination r^2 is shown as well, defined as $r^2 = 1 - SS_{res}/SS_{tot}$ with $SS_{res} = \Sigma(d_i - d(D_i))^2$ and $SS_{tot} = \Sigma(\bar{d} - d(D_i))^2$, being $\bar{d} = \Sigma d_i/n$.

4. DISCUSSION

4.A. Active layer absorption in the visible spectrum. Color phase integral absorbances

The model developed by Callens et al.[15] allows us to reanalyze the active layer absorption spectra measured by Butson et al.[13] The major strength of this model is it provides a quantitative description of the radiation-induced polymerization. Two polymer conformations were identified by Callens et al. and their model enables us to deconvolve the contribution of

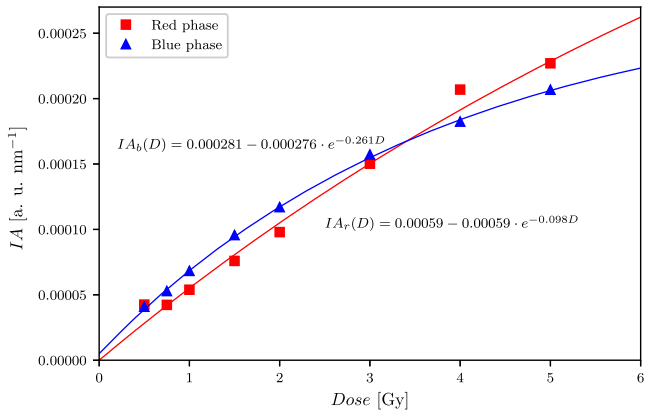

FIG. 3. Red and blue phase polymer integral absorbances and their fits to the model proposed in Eq. (4). [Color figure can be viewed at wileyonlinelibrary.com]

each of them to the total absorbance. Figure 2 shows the results of applying the model proposed by Callens et al. to the measurements published by Butson et al. measurements for an absorbed dose of 2 Gy. The model of Callens et al. was developed for the EBT3 films using unlaminated active layers. Butson et al. used commercially provided EBT2 films and their absorbance measurements were obtained by subtracting for each dose level the absorbance of a nonirradiated film. As stated by Lewis et al.,[16] both models have the same nominal thickness of the active layer and the same active fluid. The difference between them is in their substrates, but that difference is removed because of the manner in which Butson et al. treat the absorbance background. The greatest potential impact of their method is in the wavelength band between 400 and 525 nm, where the active layer attenuation is a small fraction of the total attenuation due to the yellow dye placed within the film structure. Figure 2 shows that measurements in this band fluctuate around the fit.

To quantify the radiation-induced polymer formation the integral absorbance in the visible spectrum of each polymer phase has been calculated for different doses from 0.5 to 5 Gy. This dose range is wide enough to determine the parameters of a saturation model of the integral absorbance with dose. Because of their different physical characteristics, the red phase polymer presents a strong correlation between the parameters of their ground and vibronic transitions, which is not the case with the blue phase polymer. Figures 5 and 6 show these differences. This, along with the fact that the red phase contribution is determined by the yellow dye influenced wavelength band data, implies that the red contribution presents greater uncertainties than the blue phase, as it can be seen in Fig. 3.

Devic et al.[12,14] established in an empirical way that the optical density as a function of light wavelength for the EBT models could be expressed as a sum of eight Lorentzian functions. The description of the active layer absorption spectrum published by Callens et al.,[15] supported on a theoretical basis, is basically the same as that of Devic et al.,[12] except that Devic (a) considered each absorption peak just one Lorentzian function and not a convolution of Lorentzian functions with an energy displacement due to different conjugation lengths and (b) deconvoluted the main absorption peak into two other peaks. In their 2007 work, Devic et al. published the peak integral intensities as a function of dose for the EBT model. As it could be expected these functions present a saturation shape and the absorption peaks could be classified into two groups according to their saturation rate. Their values are $k_r = 0.10$ Gy^{-1} and $k_b = 0.292$ Gy^{-1}. There is good agreement between this k_r value and the one we have determined, $k_r = 0.098$ Gy^{-1}. The k_b parameter presents a reasonable agreement if we take into account the different identification of absorption peaks proposed by Devic et al. that primarily affects the blue phase polymer.

4.B. Sensitometry model and calibration measurements

We have investigated if the light attenuation quantified by the variable d measured by the flatbed document scanner can be expressed as a dose function using a linear combination of the functions that parameterize the saturation with the dose of the integral absorbance of each polymer color phase. Figure 4 and Table I summarize the fit to our proposed sensitometric model of six calibration measurements for different production batches belonging to EBT2 and EBT3 film models. Considering an estimated d uncertainty of ± 0.003, the χ^2_n values show that the model predicts the measured dose variation in d up to fluctuations attributable to uncertainties. Taking into account the estimated uncertainties of the fit parameters and considering a confidence interval of 99.7%, just the EBT2 A08171101A batch is significantly different from the other batches. As the film manufacturer keeps the production conditions, it is difficult to assign a cause of this difference, maybe it is due to variations in the preservation conditions.

The parameters ϕ_b and ϕ_r represent the polymer color phase relative fraction to light attenuation in every scanner color channel. They not only depend on the scanner light spectra, optical filter, and electronics, but as well as on specific design features of the film model, details of the production batch, and preservation conditions, and therefore they have to be determined whenever one of these aspects change.

Using lasso regression we have been able to identify under our measurement conditions that the ϕ_b parameter can be excluded from the sensitometry model for the green and blue channels without loss of goodness of fit. Applying Eq. (12) to the green and blue channels gives a consistent result. We obtain $\rho = 0.03$ for both channels, meaning a nondetectable blue phase polymer contribution to d.

The aim of our work is to propose a sensitometric model with as few free parameters as possible and with simple mathematical relationships between them. Equation (11) describes a semiempirical model that linearly combines functions linked to light attenuation in two kinds of absorbers. These functions tell the d dependence on dose. The parameters in these dose-dependent functions have been established using a description of the light absorption physics in the active layer

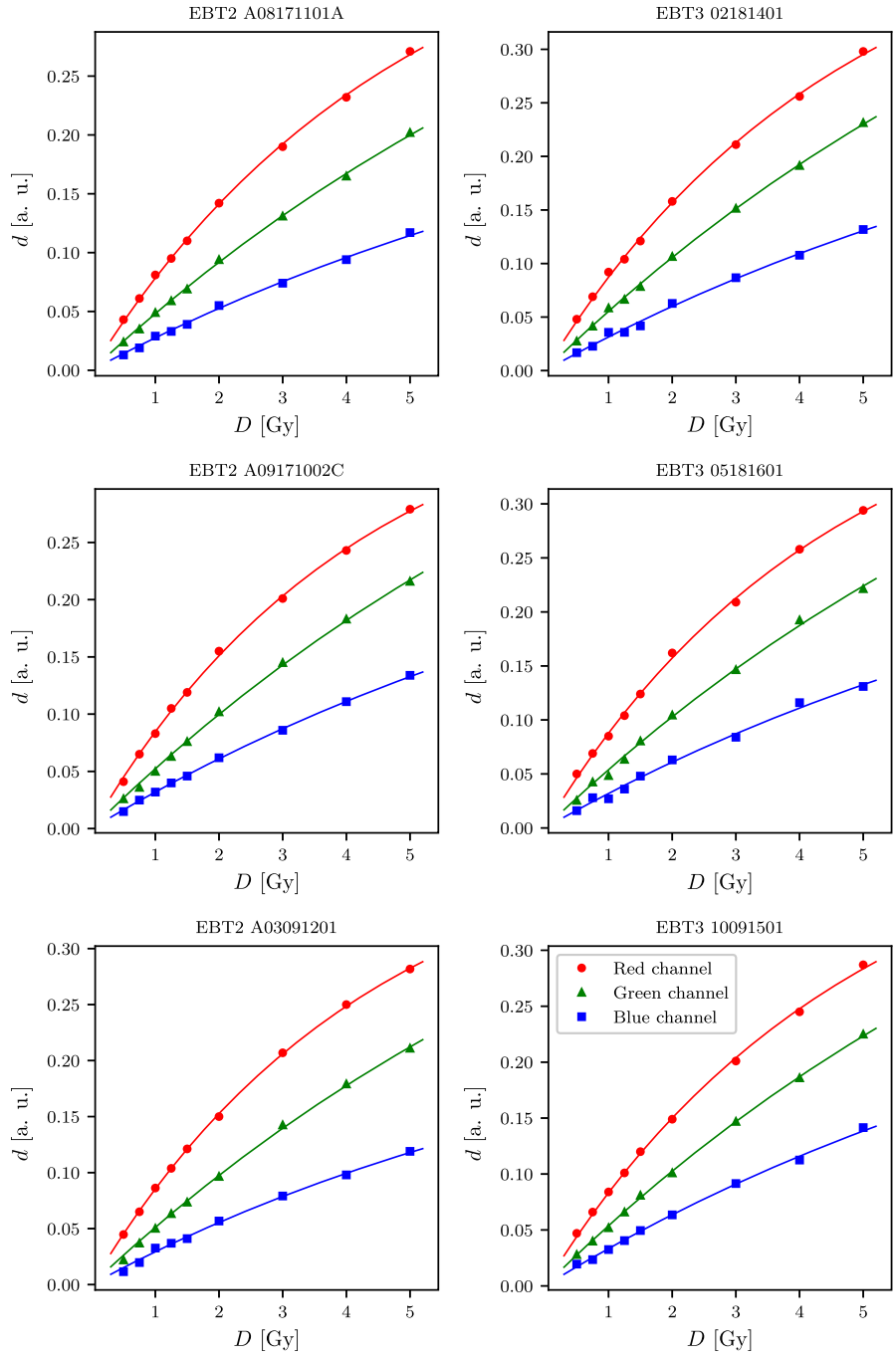

FIG. 4. Calibration measurements and their fit to the proposed model in Eq. (11). Measurement estimated uncertainties are in the order of symbol size. [Color figure can be viewed at wileyonlinelibrary.com]

of the film that allows us to separate each absorber contribution. In this way these parameters do not have to be determined using the same data that we use to calibrate a batch.

The relative abundance of the blue phase polymer to the red phase polymer ρ has been calculated modeling the digital signal the scanner produces and using its light spectrum and optical color filter specifications in conjunction with the Butson absorbance measurements. These data could not be readily available for most users. In this case, it would be possible to determine ρ fitting different batch calibration curves to Eq. (11) but letting ρ be considered as a common parameter between them. Using this approach with the six batches shown in this work we have obtained $\rho = 1.54 \pm 0.17$ in good agreement with the previously established value by means of Eq. (12), but with increased uncertainty.

A reliable sensitometric model with fewer free parameters reduces the calibration uncertainty. In order to measure a dose distribution using a radiochromic film and a flatbed scanner, a calibration curve is required. The dose measurement uncertainty will be the combination of the digital signal uncertainty measurement in field conditions, which we are not considering in this paper, and the inherent calibration

TABLE I. Fit parameters for the calibration curves shown in Fig. 4. χ^2_n stands for the χ^2 fit value normalized by the number of degree of freedom and r^2 for the regression coefficient of determination. It must be noted that $\phi_b/\phi_r = \rho = 1.67$ for the red channel. The parameter estimated uncertainties are $u_{\phi_r} = \pm 0.002$, $u_{\phi_b} = \pm 0.005$ for the red channel and $u_{\phi_r} = \pm 0.009$ for the green and blue channels.

Model	Batch	Channel	ϕ_b	ϕ_r	χ^2_n	r^2
EBT2	A08171101A	Red	0.277	0.166	0.61	0.9991
		Green		0.488	0.33	0.9993
		Blue		0.108	1.22	0.9924
	A09171002C	Red	0.291	0.174	1.26	0.9983
		Green		0.560	0.57	0.9990
		Blue		0.342	0.12	0.9994
	A03091201	Red	0.297	0.178	1.31	0.9983
		Green		0.547	0.58	0.9990
		Blue		0.271	0.62	0.9963
EBT3	02181401	Red	0.306	0.183	0.90	0.9989
		Green		0.593	0.41	0.9994
		Blue		0.336	0.96	0.9953
	05181601	Red	0.306	0.183	0.93	0.9989
		Green		0.577	1.32	0.9978
		Blue		0.342	1.49	0.9930
	10091501	Red	0.294	0.176	0.74	0.9990
		Green		0.574	0.34	0.9994
		Blue		0.357	0.51	0.9978

uncertainty. Figure 7 shows the calibration uncertainty for the three color channels estimated using our sensitometric model. The uncertainty is less than 2% for the red and green channels between 1 and 5 Gy. For the blue channel, it is about 2% for dose values above 2 Gy. Below 1 Gy for the red and green channel, 2 Gy for the blue channel, the uncertainty grows. A model with more than necessary free parameters implies higher calibration uncertainties, as some of them become poorly determined, even with fitting functions that present a qualitative behavior similar to film. Using the same calibration data presented in this work, Fig. 8 shows a comparison of the inherent calibration uncertainty for the red channel when two different sensitometric models are used: the one we propose and a model based on rational functions

$$d(D) = -log_{10}\frac{a + bD}{c + D}. \quad (13)$$

It can be seen that the rational model with three free parameters, one more than seems to be necessary for the red channel, led to higher calibration uncertainties.

Lewis et al.[16] analyzing different calibrations of films belonging to the same batch found that the dose–response curves they obtained could be related by means of linear relationships. They proposed an efficient protocol for radiochromic film dosimetry based on obtaining a generic dose–response curve for each production batch, adaptable to the current conditions using two reference films irradiated to known doses and being read under a defined set of conditions. However, when they compared the dose–response curves batch to batch or between EBT film models, they found that the relationship could not be expressed as a simple 2-point rescaling, and that an additional third point was needed. In our model, there are two parameters to be determined in every calibration: the digital signal of the nonirradiated film and the red phase polymer proportion ϕ_r, in line with the proposal[17] of studying a generic calibration curve independent of EBT film model and batch for the energies used in external radiotherapy. Bekerat et al.[18] have shown the EBT film model's overall energy response and its dependence on the active layer composition at lower energies (≤ 100 keV). A more complex model than the one we present should be required when using softer beams to account for energy dependences.

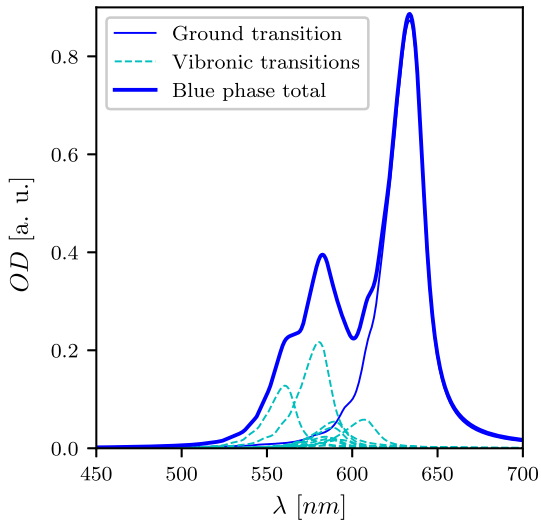

FIG. 5. Blue phase polymer absorbance breakdown by ground and vibronic transitions. [Color figure can be viewed at wileyonlinelibrary.com]

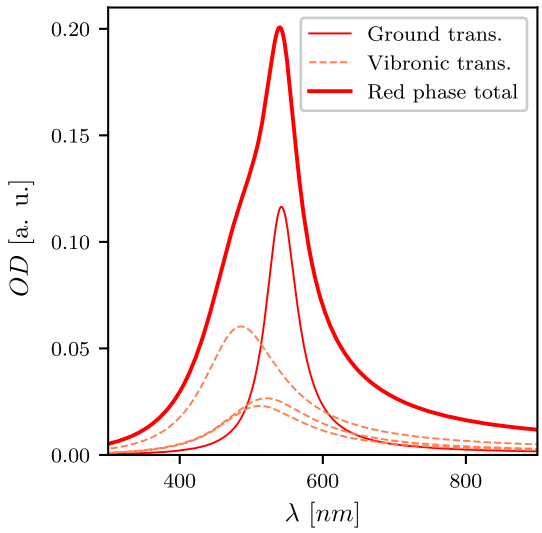

FIG. 6. Red phase polymer absorbance breakdown by ground and vibronic transitions. [Color figure can be viewed at wileyonlinelibrary.com]

5. CONCLUSIONS

In this work, we have proposed that the calibration curve for the EBT film models can be written as a linear

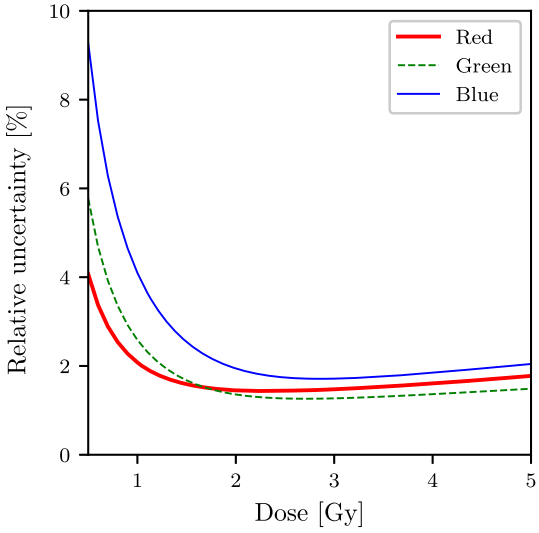

FIG. 7. Estimated inherent calibration uncertainty for the three color channels when using the proposed sensitometric model. [Color figure can be viewed at wileyonlinelibrary.com]

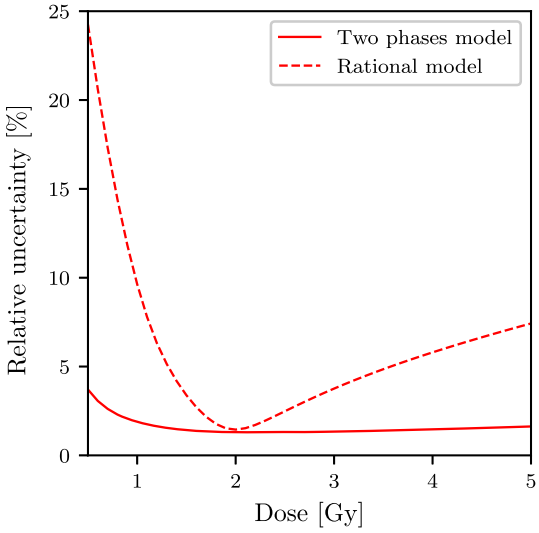

FIG. 8. Inherent calibration uncertainty comparison between the model proposed in this work and a model based on rational functions. [Color figure can be viewed at wileyonlinelibrary.com]

combination of simple functions describing the dose dependence of the integral absorbance of each polymer color phase. These functions have been established by analyzing active layer absorbance spectra data and must be a sensitive material characteristic. Therefore, they are independent of other design features of the film. It has been found as well that polymer phase relative abundance can be considered constant and that, under our measurement conditions, is negligible for the green and blue channels, that is, one of the polymer color phases does not have a significant contribution to light attenuation. Our generic sensitometric model has been applied to six different production batches belonging to two different film models. The model proposed allows calibrating a batch in terms of the active layer attenuation using just one linear coefficient. This coefficient should depend on the features of the scanner used to read out the films but as well on the specific production and preservation batch details.

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CONFLICT OF INTEREST

The authors have no conflicts to disclose.

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