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Procedure for calibration curve determination of radiochromic films for routine QA in Superficial Therapy X-Ray equipment

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ABSTRACT

This paper approaches the calibration procedure for EBT3 radiochromic films, and its precision, using a flat-bed scanner as a digitization system, for routine QA in a Superficial Therapy X-Ray machine. This paper analyzes precision in EBT3 radiochromic film calibration, using a flat-bed scanner as a digitization system, and describing routine control procedure within the framework of a quality assurance program for X-Ray equipment. Radiochromic films were cut into 5cm x 5cm squares, placed on 5cm of PMMA at 15cm source-film distance, and irradiated with several doses to obtain the calibration curve of net optical density (ODn) as a function of dose, and dose uncertainties were computed by residual analysis. The calibration curve fits a fourth-degree polynomial function, with uncertainties of 2.10%, and 2.48% for the dispersion in the dose measurements in the films; we also considered a 3.5% uncertainty in dose measurements due to the use of an ionization chamber, for a net uncertainty (one sigma) of 4.77 % in the dose value. The calibration curve of the EBT3 films was obtained by a procedure that establishes the ODn as a function of the dose delivered by the X-Ray machine, based on the traceability of the dose

Keywords: Superficial Therapy X-Ray, Radiochromic Film, EBT3, Optical Density, Calibration Curve.

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INTRODUCTION

Radiographic films are used as a quality control instrument for relative and absolute dosimetry in radiation-emitting equipment, but their use can pose some drawbacks due to their processing [1]. To avoid this process, we can use radiochromic films, where ionizing radiation interacts with the active layer of this type of film, which generates a polymerization process that leads to a change in its optical properties; being this a process that stabilizes over time [2].

Therefore, it is possible to establish a relationship between the dose delivered to the film during exposition and the darkening level on it. To find this relationship, other authors use different digitization systems for evaluating these devices in terms of their response during the calibration process of radiochromic films, quantifying the influence the device has on the global processing of the film, since its use is itself a source of uncertainty in the determination of the dose ([3], [4], [5], [6]). Some authors have studied and elaborated a procedure for calibration curve determination for this type of film, establishing a formalism from the relationship of the variables: irradiation dose and response of the film, by graphing the response as a function of dose ([7], [8], [9], [10]) or the dose as a function of response ([11], [12], [13], [14]).

From the information presented in scientific literature, it is important to analyze each calibration procedure and the components used in the dosimetric evaluation of radiochromic films, according to available resources, to obtain the best precision in dose measurement.

This paper deals with the calibration procedure for EBT3 radiochromic films based on OD determination as a function of dose, using a flat-bed scanner as a digitization system, for routine QA in a Superficial Therapy X-Ray machine.

MATERIALS AND METHOD

The radiochromic films used in this study were Gafchromic EBT3 (Ashland Inc., Wayne, NJ. Lot: 05171701), which were cut into 5cm x 5cm squares and placed on 5cm of PMMA. The X-ray source distance to the surface of the film was 15cm. Dose values of 0, 1.1, 1.5, 2, 2.5, 3, 4, 5 and 6 Gy, were delivered to the films, taking only one film per dose.

The irradiation process of the radiochromic films was conducted using an Xstrahl 150 X-ray Superficial Therapy equipment (Xstrahl Limited, Surrey, U. K), with a 5cm diameter applicator cone, and using a nominal energy of 150 kVp. The calibration of the equipment follows the recommendations of AAPM TG61 protocol [15], obtaining a reference for dose rate value of 392.34 cGy/min with the above-stated parameters.

Figure 1 shows the configuration used for the calibration of radiochromic films; image a) represents the configuration for determining the reference dose using a FARMER-type ionization chamber (PTW-Freiburg, Germany), considering an uncertainty in dose measurements of 3.5% at one sigma [15]; and image b) shows the position of the film on the phantom in the irradiation process.

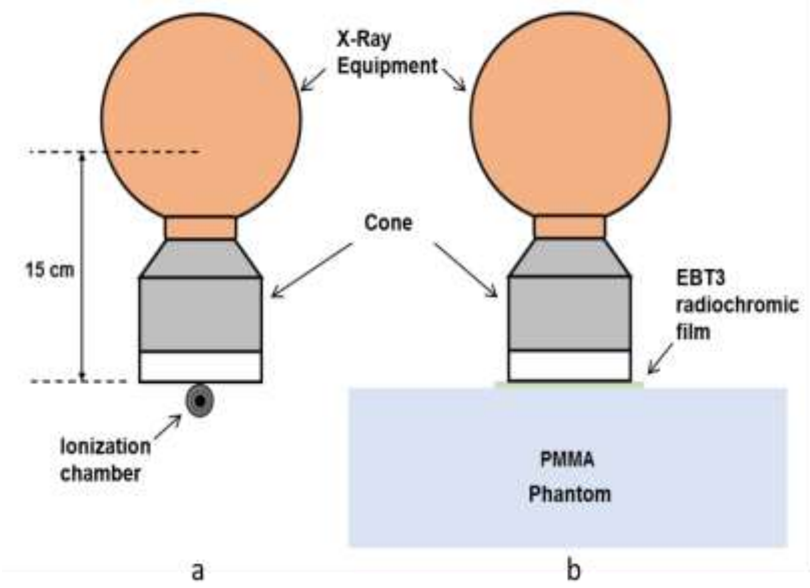

Figure 1: Configuration for determining the irradiation dose of radiochromic films. a) Estimated dose with the ionization chamber in air b) Irradiation of radiochromic films.

An Epson-Expression-11000XL flat-bed scanner, (Seiko Epson Corp., Nagano, Japan) was used to digitize the irradiated films. The scanning process was simultaneous for all films, positioning them in the central region of the scanner and in the same orientation to avoid any polarization effect on them ([16], [17]). Settings in the scanner: in transmission mode, RGB at 48 bits (16 bits per color) and 150 dpi resolution. Furthermore, no correction tools were used, and the image was saved in TIFF format.

From the images obtained with the scanner, we used the Image J software (National Institutes of Health, USA) to perform intensity measurement using only the red channel. For a region of interest (ROI) of 1cm x 1cm in each measurement, we obtained the average value of intensity in the ROI with its standard deviation, considering 5 intensity measurements on each film, to account for possible non-uniformities of the film and imperfections in the glass surface of the scanner, as described by Devic et al., 2016 [8]. The determination of the net optical density (ODn) and its associated uncertainty was according to Devic et al., 2004 [4], initially defining an average intensity value in the unirradiated film:

$$\bar{I}_0 = \frac{\sum_{i=1}^{5}\left({I_{0,i}}/{\sigma_i^2}\right)}{\sum_{i=1}^{5}\left({1}/{\sigma_i^2}\right)} \qquad (1)$$

Where $\bar{I}_0$ and I_0 are the average intensity and the intensity measured at each ROI of the unirradiated film, and σ is the standard deviation of each intensity measurement.

Thus, the following expression was used to calculate the ODn, considering I_g as the intensity of each ROI in the irradiated film:

$$ODn = \log_{10}\left(\frac{I_0}{I_g}\right) \qquad (2)$$

To determine the uncertainty associated with each ODn, we used uncertainty propagation, ignoring cross correlations between film pieces from the same sheet [18]:

$$\sigma_{ODn} = \frac{1}{ln10}\sqrt{\frac{\sigma_{I_0}^2}{{I_0}^2} + \frac{\sigma_{I_g}^2}{I_g^2}} \qquad (3)$$

From the numerical results of this procedure, ODn is defined as a function of dose. To determine the best fit in this graph, the following parameters were considered: the correlation coefficient, the F-test, and normality of residuals using the Anderson-Darling method [19].

The net uncertainty of dose was determined by residual analysis, calculating two main associated components. The first component is the uncertainty associated with the calibration curve, based on the differences between the average doses measured on the film, and the actual dose delivered and determined by ionization chamber measurement, is expressed by the equation [20]:

$$u_{curva}(\%) = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{\bar{D}_i - D_{c,i}}{D_{c,i}} * 100\right)^2}{n}} \qquad (4)$$

Where, n is the number of plotted points, $\bar{D}$ is the average dose measured on the film, and D_c is the irradiation dose determined with the ionization chamber.

Moreover, the second component is the contribution to uncertainty due to the variation in the measurement of the dose in the films. This refers to the difference between the dose determined by the ionization chamber and the dose obtained in each ROI defined on the film. The calibration curve quantifies the dose of each ROI. The following equation describes this component:

$$u_{film}(\%) = \sqrt{\frac{\sum_{i=1}^{n_{med}}\left(\frac{D_i - D_{c,i}}{D_{c,i}} * 100\right)^2}{n_{med} - n_{pol}}} \qquad (5)$$

Where, n_{med} is the number of total readings made on the films, n_{pol} is the number of parameters in the fit polynomial, D is the dose reported in each reading made on the films, and D_c is the actual dose at which the film was irradiated and defined with the ionization chamber.

RESULTS AND DISCUSSION

The evaluation of uncertainties in the calibration of a dosimetry system is important to establish precision in the determination of the dose in routine QA processes, such as: the verification of the dose in clinical radiotherapy procedures, in-vivo dosimetry and quality control procedures. ([8], [12], [13]).

Figure 2 shows the behavior of the variation of the ODn (σ) uncertainty as a function of dose. The uncertainty values are at one sigma.

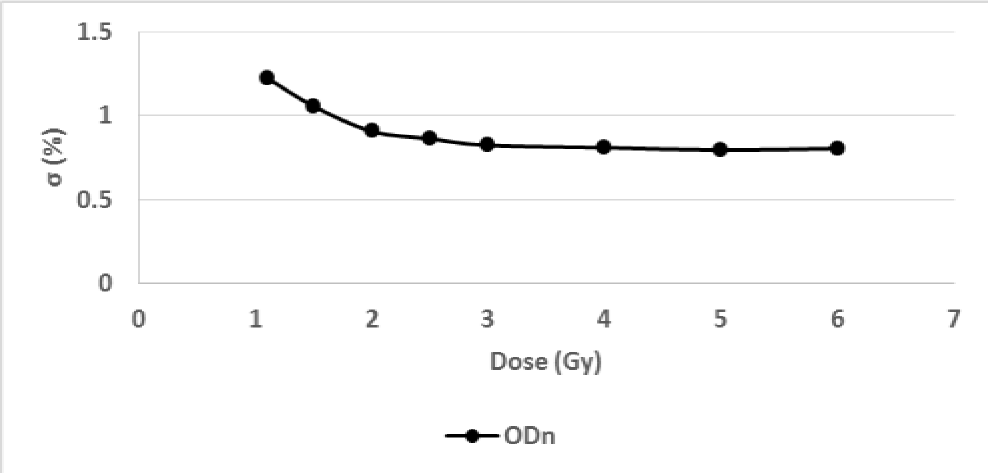

Figure 2: Variation of the ODn (σ) uncertainty as a function of the dose.

An important aspect to mention is that the limits in the dose range used in this study are dependent on several factors. The lower value (1.1 Gy) was due to the energy and capabilities of the X-ray equipment, which does not allow irradiation below 0.25 min, and the final dose (6.0 Gy) was determined by the working range of the red channel, associated with the sensitivity curve presented in the literature [18]. The variations in the ODn uncertainties in figure 2 show a behavior that is similar to the same curve for films irradiated with megavoltage energy; where the uncertainty of the ODn is greater at low doses, until reaching a stable value by increasing the dose. The above is a qualitative comparison, since these values depend on the digitization equipment used [4].

Figure 3 shows the calibration curve of the films and the proposed fit, resulting in a fourth-degree polynomial; table 1 shows the fit parameters and the result of F-test.

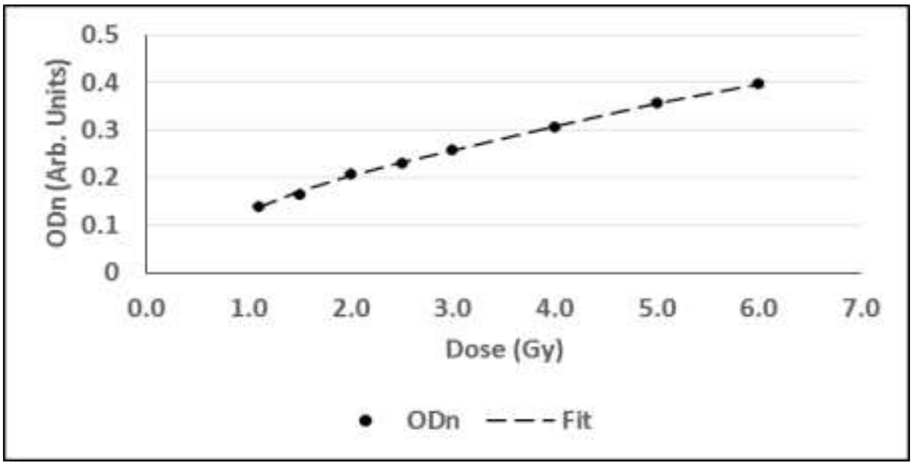

Figure 3: Calibration curve for EBT3 radiochromic films for the X-ray equipment. Error bars are estimated at 2 sigma.

The calibration curve fitting process, established by Devic et al. ([4], [7], [8]), proposes a graph of Dose as a function of the ODn, and establishes a process for fitting the data, using a "Levenberg-Marquardt" Quasi-Newton minimization method, and evaluating the fit using the χ^2 test, as proposed by Hwang et al. [9]. These methods define that the dose uncertainties depend on the range on which they are founded, due of the fact that the fit parameter uncertainties and the dose uncertainty are calculated using uncertainty propagation because the noise-signal ratio of the relation D(ODn) generates higher uncertainty values at a low dose.

In this analysis, we proceeded as shown in Figure 3 (ODn as a function of Dose). Since the calculation of the doses delivered to the films was according to the formalism presented in the AAPM protocol [15], in this case the dose is determined by an ionization chamber, traceable to a secondary calibration laboratory. For the relation ODn(D), the best fit was determined by the correlation coefficient and the F-test (Table 1). The test shows that residuals follow a normal distribution, which helps to avoid a residual trend, as it would cause an increase in the total uncertainty in the dose. All the ODn values obtained in each ROI are plotted instead of their average value per film; this means that in estimating the fit parameters, the dispersion of the measurements in each film was considered.

Table 1: Result of regression process.

Fit Parameters*	Value	F_{cal}	F-critical value
a	0.00	72680.05	$4.74x10^{-68}$
b	0.1652		
c	-0.0456		
d	0.0079		
e	-0.00051		

* Fit parameters of the function: $ODn(D) = a + bD + cD^2 + dD^3 + eD^4$.

The calculation method used for determining the contribution of the uncertainty to the dose for the calibration curve and variation of the measurement in the film (equations 4 and 5 respectively), generates a single value for the entire dose range. The residuals analysis presented in this study is based on an overestimation of the uncertainty of the dose in the central area and an underestimation of the uncertainty of the dose at the extremes of the dose range; for that reason, is not possible to extrapolate values in the curve [20].

The uncertainty values in doses found were 2.10% for the adjustment curve and 2.48% for the dispersion in the dose measurements in the films, also considering an uncertainty of 3.5% in the measurements made with the ionization chamber, obtaining a net uncertainty (one sigma) of 4.77% in the dose value. This information is summarized in Table 2.

Table 2: Results of the uncertainty estimation process.

u_{fit}	u_{film}	u_{cal}	u_{total}*
2.10 %	2.48 %	3.50 %	4.77 %

* Only the sources of uncertainties presented in the table.

The EBT3-scanner combination for radiochromic film dosimetry presented an acceptable uncertainty value for dose determination, when compared to other studies where the same type of film and scanner was used, without considering the uncertainty of the irradiation dose, because a megavoltage X-Ray equipment was used [18]. Additionally, the method applied for the determination of the curve shown in Figure 3 and Table 1 has statistical significance according to the results of the validation tests for the conditions and the dose range in which this study was conducted.

CONCLUSION

The calibration curve of the EBT3 films was obtained by a procedure that establishes the ODn as a function of the dose delivered by the X-Ray machine, based on the traceability of the dose. Residual analysis was used for determination of the uncertainty of the calibration curve and the dispersion of the measurement of the dose in the film; in other words, a value was obtained for each of these uncertainty sources over the entire dose range. It is important to notice that in this proposed adjustment the dispersion at low doses should be studied to avoid a considerable overestimation of the net uncertainty.

The methodology presented in this paper can be included in a QA program for determination of dose curve of a film set. As stated by recent references regarding this type of analysis in film dosimetry, the fact of extending this methodology for determining the calibration curve to other qualities of radiation beams can be valued for future work.

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