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Technical note

Monte Carlo uncertainty analysis of dose estimates in radiochromic film dosimetry with single-channel and multichannel algorithms

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ABSTRACT

Purpose: To provide a multi-stage model to calculate uncertainty in radiochromic film dosimetry with Monte-Carlo techniques. This new approach is applied to single-channel and multichannel algorithms.

Material and methods: Two lots of Gafchromic EBT3 are exposed in two different Varian linacs. They are read with an EPSON V800 flatbed scanner. The Monte-Carlo techniques in uncertainty analysis provide a numerical representation of the probability density functions of the output magnitudes. From this numerical representation, traditional parameters of uncertainty analysis as the standard deviations and bias are calculated. Moreover, these numerical representations are used to investigate the shape of the probability density functions of the output magnitudes. Also, another calibration film is read in four EPSON scanners (two V800 and two 10000XL) and the uncertainty analysis is carried out with the four images.

Results: The dose estimates of single-channel and multichannel algorithms show a Gaussian behavior and low bias. The multichannel algorithms lead to less uncertainty in the final dose estimates when the EPSON V800 is employed as reading device. In the case of the EPSON 10000XL, the single-channel algorithms provide less uncertainty in the dose estimates for doses higher than four Gy.

Conclusion: A multi-stage model has been presented. With the aid of this model and the use of the Monte-Carlo techniques, the uncertainty of dose estimates for single-channel and multichannel algorithms are estimated. The application of the model together with Monte-Carlo techniques leads to a complete characterization of the uncertainties in radiochromic film dosimetry.

1. Introduction

The characteristics of radiochromic film (RCF) such as its near tissue equivalence, small dependence on both energy and dose rate and high spatial resolution [1] make RCF the choice in many dosimetry applications. In particular, these characteristics make RCF a very interesting dosimeter when the electronic equilibrium is lost or high resolution dosimetry is required. Small fields found in radiosurgery or SBRT, highly inhomogeneous fields found in IMRT or VMAT treatment verifications and high dose gradients of brachytherapy treatments are frequently measured with RCF [2–5].

The exposition of RCF to ionizing radiation produces a response, the darkening of the film. This response is usually read with flatbed color scanners [6,7]. These devices produce three different color channels per reading, red-green-blue or RGB. In order to be able to convert film responses of a film lot to absorbed doses a calibration should be performed. Several protocols for the calibration of a RCF lot have been described in the bibliography [8,9,1,10–16]. The aim of these protocols is to obtain sensitometric curves relating film responses in every channel and doses.

Once the calibration of a film lot has been performed, the film responses found in any irradiated film of the lot may be converted to a dose map. The single-channel algorithms obtain the doses with the application of the sensitometric curve to film responses of the selected channel [1,10,11,14,17]. The multichannel algorithms work with the film responses of the three available channels and the three sensitometric curves simultaneously to obtain the doses [13,14]. Some advantages of the multichannel algorithms include the reduction of noise and the partial mitigation of the scanning lateral artifact.

The target of the dosimetric process with RCF is to obtain a dose estimate for every pixel of the evaluated film, exploding the high resolution of the dosimeter. However, every stage of the calibration procedure is affected by uncertainties. Moreover the final estimation of the dose map is carried out by means of the results of the calibration

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process and by employing the selected algorithm (single-channel or multichannel). In order to calculate the uncertainty of the final dose estimates, the uncertainties arising from the calibration procedure, the uncertainties of the evaluated film responses and how the selected algorithm manages all the uncertainties should be taken into account. Previous works have evaluated the uncertainty in dose estimates of RCF dosimetry with single-channel algorithms [1,10,11,17,18] and the law of propagation of the uncertainties [19]. However, the analysis and quantification of the uncertainty in dose estimates when multichannel algorithms are employed is still an unsolved issue. In the case of these algorithms a complete uncertainty analysis should comprise the characterization of the film responses in the three reading channels and their correlations [20] as well as the particularities of the multichannel algorithms.

In this paper we present a multi-stage model for uncertainty analysis of the dose estimates in RCF dosimetry.The model is valid for single-channel and multichannel algorithms, so it is applied simultaneously to both kinds of algorithms. Based on this model, the probability density functions (PDFs) of the input magnitudes are characterized and they are propagated through the model with Monte-Carlo techniques. The resulting uncertainties of every stage of the model are calculated, presented and analyzed. In this way, the uncertainties of the dose estimates are obtained and compared for single-channel and multichannel algorithms. Finally, the implications of the scanner employed for the reading process are studied and their impact on the final uncertainty of the dose estimates is discussed.

2. Material and methods

2.1. Experimental measurements

Two lots of Gafchromic EBT3 films (Ashland Inc, Russell, USA) with serial numbers #04141403 and #11021501 were calibrated and analyzed in this work. One calibration film per lot was considered and these films were manipulated according to recommendations [21]. Every calibration film was divided in eight pieces of 20.4 cm x 2.9 cm. The pieces of the two calibration films were exposed with the same setup. They were placed at a deep of 10 cm in a slabbed equivalent water phantom (RW3) with a source to surface distance of 90 cm. The projection of the crosshair was marked in every piece for alignment purposes. The pieces were irradiated with beams of a nominal energy of 6 MV and a field size of 20 cm × 20 cm, with doses ranging from 0 to 10 Gy. The calibration film of the lot #04141403 was irradiated using a DHX Clinac (Varian, Palo Alto, USA), while the calibration film of the lot #11021501 was irradiated in a Varian Trilogy linac.

Prior to the irradiation of the pieces of the calibration films, the output of the linac was measured using the same setup that was employed for the irradiation of the film pieces. In the case of the DHX Clinac an A12 ionization chamber (Standard Imaging, Middelton, USA) and a PC Electrometer (Sun Nuclear Corp., Melbourne, USA) were employed, while in the case of the Trilogy linac a PTW Farmer 30013 chamber and a PTW Webline Unidos electrometer (PTW, Freiburg, Germany) were used.

At least four hour post-irradiation of the film pieces, they were read in an EPSON V800 scanner (Seiko EPSON Corp., Nagano, Japan) in portrait orientation. In order to avoid the undesired inter-scan variability, all the pieces of the same calibration film were digitized together. The marks of the crosshair projection onto the pieces were aligned with the center of the bed of the digitizer to minimize the lateral scanning artifact. The images were acquired with all the corrections turned off and were saved in tiff format with a resolution of 72 dpi. The digitizer was switched on half and hour prior to the scanning session and seven open scans of the whole field of the bed were performed to warm up the system before the acquisition of the images of the calibration films. Finally, the images were loaded into Matlab (Mathworks, Massachusetts, USA) and analyzed with in-house software.

Additionally another calibration film from the lot #11021501 was irradiated in the DHX Clinac with doses ranging from 0 to 11 Gy. The exposition and the reading protocols for this film were the aforementioned protocols, except for the post-exposure time, higher than 48 h. This film was read in four different scanners: two EPSON 10000XL and two EPSON V800. The aim of this procedure was to evaluate the influence of the reading devices in the final uncertainty analysis achieved with single-channel and multichannel algorithms.

2.2. Uncertainty analysis: from the law of propagation of uncertainty to the Monte-Carlo approach

Traditionally the law of propagation of uncertainty is employed to obtain the combined uncertainty $u_c(y)$ of a magnitude y from the known uncertainties $u(x_i)$ of the magnitudes x_i $i = 1,\ldots,N$, with covariances $u(x_i,x_j)$ between the $x_i s$ magnitudes, and related to y by the expression $y = f(x_i)$. Thus, by employing Eq. (1) the combined uncertainty of the output magnitude y is obtained as the positive root of its variance $u_c^2(y)$:

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) u(x_i,x_j) \tag{1}$$

With this approach, the uncertainty of the output magnitude may be expressed as the standard uncertainty, $u_c(y)$, or as a confidence interval by employing a proper coverage factor, as it is widely described in [19]. However, in certain circumstances this approach may lead to inappropriate results due to an inadequate representation of the linearity of the problem or a deviation from the Gaussian behaviour [23].

The Monte-Carlo approach [22–24] to uncertainty analysis is intended to deal with complex relationships between the input magnitudes and to take into account any nonlinearity present in the model. Also the correlation between the input magnitudes and the deviations from the Gaussian behaviour are contemplated in this approach. It is worth to mention that these Monte-Carlo methods do not realize a probabilistic calculation of the uncertainty. Instead, they are intended to propagate the PDFs of the input magnitudes throughout a previously established model to obtain a numerical realization of the output magnitude(s) PDF(s), as it is schematized in Fig. 1. From this output PDF, the uncertainty may be estimated as a standard deviation or a confidence interval [23,24]. The model is intended to relate the input and the output magnitudes, including the equations or algorithms that lead to the calculation of the output magnitude(s) from the input magnitudes. For complex uncertainty evaluations a model composed by several stages may be employed [23,24]. Every stage of the model may be independently analyzed, and, moreover, the numerical output of the firsts stages may be considered as the input for the next stages, and so, until the whole model is traveled, and, finally, the numerical realization of the output magnitude PDF is obtained. Previously to the application of the Monte-Carlo techniques to the proposed model, the PDFs of the input magnitudes should be investigated and properly characterized, including the correlations between them, in order to realize a correct

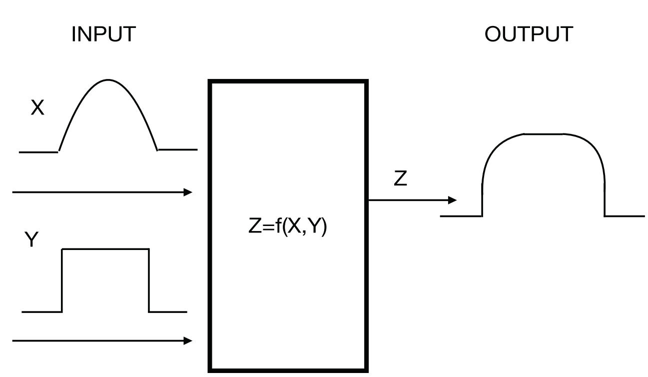

Fig. 1. Scheme of the Monte-Carlo approach for uncertainty estimation.