Evaluation of EBT-XD Radiochromic Films for High-Dose Radiotherapy patient specific Quality Assurance

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Abstract: This study evaluates the performance of EBT-XD radiochromic films for patient-specific quality assurance (QA) in high-dose treatments such as Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT). These films are ideal for measuring dose distribution due to their high resolution and energy independence. However, uncertainties may arise from interactions between the film and the scanning device. The objective of this research was to characterize the performance of EBT-XD films using an EPSON Expression 12000XL scanner in transmission mode. Key film parameters such as polarization effects, dose range, and calibration accuracy were analyzed. Results showed no significant polarization effects, and transmission mode provided better dose differentiation. Calibration was validated with less than 3% relative discrepancy for most test fields. The performance of EBT-XD films was compared with an electronic portal imaging device (EPID) across three clinical cases. The absolute gamma passing rate (PR) obtained was comparable or superior to the EPID, and the films offered a more comprehensive representation of the dose distribution, highlighting their value as an additional QA tool in highly modulated radiotherapy treatments.

I. INTRODUCTION

Radiotherapy is an oncology treatment that uses ionizing radiation to treat various types of tumors. One of its primary modalities is external beam radiotherapy (EBRT), which uses a highly collimated ionizing beam from an external source to treat tumor cells.

In order to confirm that the treatment is carried out safely and that the radiation is delivered in a controlled and efficient manner, patient-specific quality assurance (QA) is performed to minimize potential discrepancies between the dose calculated by the treatment planning system (TPS) and the dose actually delivered by the linear accelerator.

The methods and machines used to carry out the QA vary according to the dose delivered and the treatment plan. However, one of the most common devices used to measure the delivered doses are ionization chambers, which provide us with the average value of the dose deposited in their sensitive volume. This leads to difficulties in the measurement of doses in the case of small or highly modulated fields [1]. Another measurement device are radiochromic films, whose active principle is diacetylene monomers that polymerize when exposed to radiation. This process results in a darkening of the film proportional to the applied radiation dose [2].

The high resolution of the radiochromic films, their suitability for working with small fields, low energy dependence (in the 100keV – MV range) and the fact that they are a water equivalent material [3] are some of the reasons that make them ideal for measuring the dose distribution and performing patient-specific QA in Stereotactic Radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT). These radiotherapy treatments deliver high doses of radiation per session compared to conventional radiotherapy, targeting a highly localized region of interest (ROI) in a small number of sessions [4] [5].

Despite the advantages of using radiochromic films, there are a number of limitations that must be considered when using them for patient-specific QA. Therefore, we can consider two main sources of uncertainty when using radiochromic films [2]: variations in the radiochromic films and possible interactions between film and scanner. In addition to performing a film calibration each time a new batch of the radiochromic film is used, specific procedures must be implemented in order to reduce the various sources of uncertainty considered.

Radiochromic films should be handled with care, with gloves and in a controlled atmosphere, as dust and scratches in the films can affect the system response. On the other hand, once exposed to radiation, the darkening of the film continues indefinitely (at a slower rate), so it is advisable to wait at least 24 hours for the polymerization to stabilize before analyzing the films [2]. Finally, the dose range used should be known in order to use a film model that works accurately in the range of interest. In the case of SRS and SBRT treatments, it is recommended to work with EBT-XD radiochromic films, since they are designed for an optimal performance in the dose range of 0.4 to 40 Gy [3], therefore making them more suitable for these type of treatments compared to other film models [6].

Effects caused by the interaction between the radiochromic film and the scanning device have been quantified and reduced in the last years thanks to improvements in scanners and the use of newer film models. On the other hand, due to the fact that films can polarize light, some film models show a difference in the system response depending on the film orientation in the scanner bed [7], therefore it is necessary to check if the films used show polarization effects and if so, to always scan them in the same orientation. Finally, the analyzed dose range also shows a dependence with the used scanning mode (transmission or reflection): while the reflection mode allows us to increase the sensibility in low doses, it also reduces the dose dynamic range, therefore it is recommended to use the transmission mode when working with high doses [2].

The purpose of this study is to analyze the suitability of EBT-XD radiochromic films using an EPSON expression 12000 XL as a scanning device to perform patient-specific QA for SRS and SBRT treatments. We will study the response of the films when exposed to high doses and highly modulated fields, taking into account the aforementioned uncertainty factors and comparing the accuracy of this system with the electronic portal imaging device (EPID) when measuring the patient-specific QA of different treatment plans using the gamma passing rate (GP) as a measure to compare the calculation accuracy for each patient-specific QA measurement device [8].

II. MATERIALS AND METHODS

In order to perform the required measurements, EBT-XD (lot. 10172301) and EBT-4 (lot. 07192301) radiochromic films were used in a real water phantom (RW3). The films were irradiated using a Varian TrueBeam linear accelerator (Fig. 1). Unless otherwise noted, there was a 5 cm layer of RW3 below the exposed film and a 10 cm layer of RW3 on top of it, with a surface source distance (SSD) of 90 cm (therefore a film-source distance of 100 cm) and the films were exposed to 6 MV flattening filter free (FFF) photon beams.

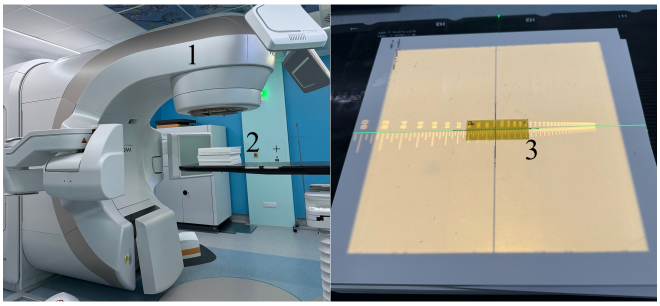

FIG. 1: Linear accelerator (1), water phantom (2) and a close-up of the radiochromic film before irradiation (3).

After irradiation, the films were analyzed using an EPSON expression 12000 XL scanner, along with the Transparency Unit accessory (B12B819221) to scan the films in both reflection and transmission modes. The films were scanned using standard procedures in film dosimetry [2]: using a 48 bit RGB mode, with a 75 ppp resolution and all the image processing tools turned off. The resulting file was saved in a Tagged Image File Format (TIFF) to preserve the detail and color in the high quality image.

To obtain an accurate result lecture, `radiochromic.com` was used, a film analysis software that allows to perform different types of measurements and corrections in radiochromic film dosimetry, thus reducing the uncertainty factors related to the interaction between the radiochromic film and the scanning device (inter-scan variations, noise of the scanner signal...)[2].

A. EBT-XD general characteristics

We focused in analyzing specific issues related to the use of EBT-XD films when realizing patient-specific QA in SRS and SBRT treatments. These were:

1. **Polarization effects.** Since they are not specified in the EBT-XD film characteristics [3], a set of three EBT-XD films was exposed to a dose of 2.5 Gy. The films were scanned from both sides using reflection and transmission scanning modes in order to determine if any differences in the pixel value (PV) measurements were observed.

2. **Differences between transmission and reflection scanning modes.** In order to evaluate whether scanning the films in transmission mode allows us to increase the dynamic range of the films, a set of twelve EBT-XD films was exposed to the following doses: 1.25, 2.50, 3.75, 5.00, 7.50, 10.00, 15.00, 20.00, 30.00, 40.00 and 50.00 Gy, along with an unirradiated film. The dose-PV curves for each scan mode (transmission and reflection) were compared.

3. **Dose range.** To evaluate whether the EBT-XD radiochromic films allow us to work in a higher dose range compared to the EBT-4 films, a set of twelve EBT-4 films was exposed to the following doses: 1.14, 2.27, 3.39, 4.53, 6.80, 9.06, 13.59, 18.12, 27.18, 36.24, and 45.30 Gy, along with an unirradiated film. After irradiation, the films were scanned in transmission mode to compare the dose-PV curve for EBT-4 films with the curve previously obtained for EBT-XD films scanned in transmission mode.

B. Calibration and verification

After characterizing key film properties and setting up the analysis methodology, a calibration set was obtained for the EBT-XD films. To do so, a set of seven 20×3 cm^2 EBT-XD films was exposed to 25×25 cm^2 fields of 6 MV with flattening filter (FF) at the following doses: 2.54, 5.08, 10.16, 20.33, 40.65, and 50.81 Gy along with an unirradiated film. The films were then scanned in transmission mode in order to obtain the PV-dose calibration curve.

Once the calibration curve was obtained, its accuracy was evaluated by measuring the dose of seven FFF fields with different known parameters (field shape, dose, SSD and film depth) using 4×4 cm^2 EBT-XD films.

C. Comparison with other measuring devices

EBT-XD radiochromic films in a cylindrical water phantom were irradiated with three different treatment plans corresponding to a brain tumor (SRS), a heart irradiation (cardiac radioablation using SBRT [9]) and a lung tumor (SBRT).

The images obtained were scanned in transmission mode and uploaded to the `radiochromic.com` software for analysis using the previously established calibration for the EBT-XD films. For both the radiochromic film and the EPID lecture of each treatment plan an evaluation of the relative Gamma Passing Rate (PR) [8] was conducted, applying a 2% dose range and a 2 mm distance range [8].

III. RESULTS

A. EBT-XD general characteristics

1. **Polarization effects.** As shown in Table 1, there was no significant polarization effects in any of the scan modes used:
   - For the reflection mode, we obtained an average PV of 0.734 with a 0.006 standard deviation in side A and an average PV of 0.731 with a 0.002 standard deviation in side B.
   - For the transmission mode, we obtained an average PV of 0.864 with a 0.001 standard deviation in side A and an average PV of 0.870 with a 0.002 standard deviation in side B.

	Reflection				Transmission			
	Side A	σ	**Side B**	σ	**Side A**	σ	**Side B**	σ
Film 1	0.727	0.007	0.729	0.007	0.846	0.007	0.869	0.007
Film 2	0.737	0.007	0.733	0.007	0.865	0.006	0.871	0.006
Film 3	0.737	0.007	0.739	0.009	0.863	0.006	0.868	0.009

TABLE I: Normalized PV lecture for each side of the films exposed to a dose of 2.5 Gy. Both reflection and transmission scans are shown. Each row corresponds to one film.

2. **Differences between transmission and reflection scanning modes.** Fig. 2 shows the dose-PV curves for the EBT-XD film set. It can be observed how reflection mode shows a saturation of the PV when higher doses are delivered, whereas the PV lecture for transmission mode does not show this saturation for the recorded higher doses. As the reflection mode shows more difficulties in successfully differentiating higher doses than the transmission mode, transmission scanning mode was used for the following measurements.

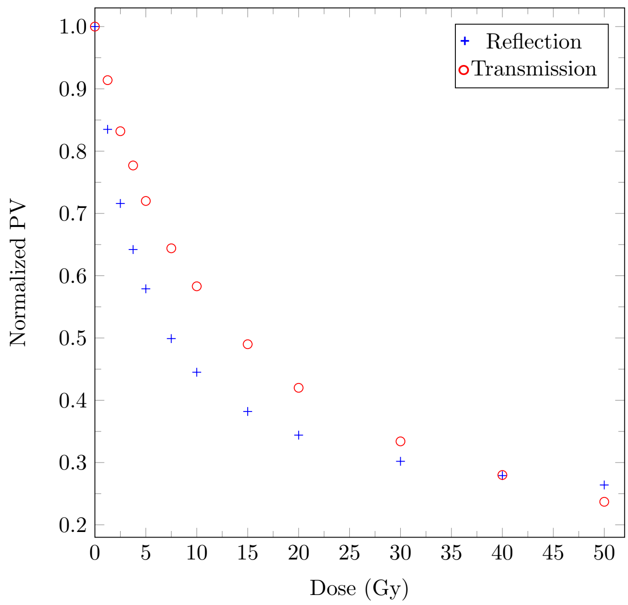

FIG. 2: Normalized PV as a function of the exposed dose (Gy) for reflection (blue) and transmission (red) scan modes. Error bars are not included as they are smaller than the size of the figure points.

3. **Dose range.** Fig. 3 shows the dose-PV curves for EBT-XD and EBT-4 film sets. The graph shows how EBT-4 darkens faster when exposed to radiation (i.e. the PV for EBT-4 film gets smaller quickly).

   Similar to the evaluation of the differences between the transmission and reflection scanning modes, the suitability of the EBT-XD films to work at high doses was also assessed by evaluating the curve saturation at high doses. A linear regression for points exposed to doses greater than 13 Gy was performed on each curve to visually estimate the slope differences in the high dose region.

   In Fig. 3 it can be seen that the slope for the EBT-4 is smaller (in absolute value) than that for the EBT-XD. Therefore, the EBT-4 films have a lower sensibility at higher doses compared to the EBT-XD films.

B. Calibration and verification

The calibration was successfully performed following the procedures detailed on [2].

The results obtained are presented in Table II. Doses between 1.8 and 41 Gy (num. 1-6) were successfully an-

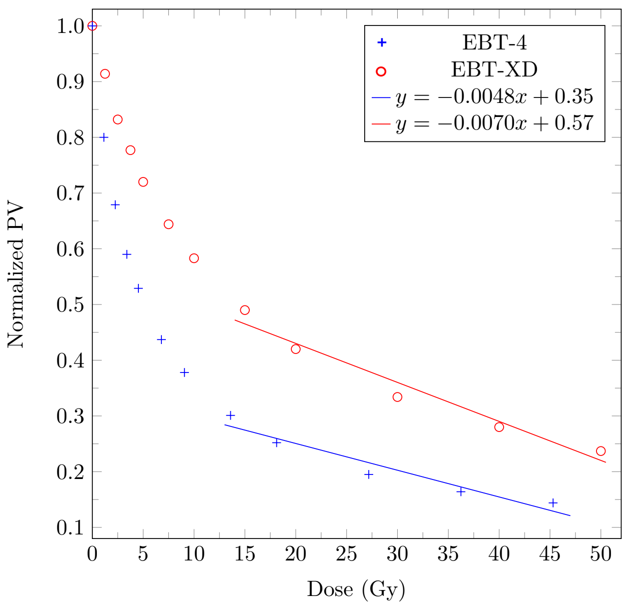

FIG. 3: Normalized PV as a function of the exposed dose (Gy) for EBT-XD (red) and EBT-4 (blue) films scanned in transmission mode along with a linear regression for doses higher than 13 Gy. Error bars are not included as they are smaller than the size of the figure points. R^2 values are not included as a linear dependence is not expected.

alyzed, with different field sizes, film depths and SSD, obtaining a threshold relative discrepancy lower than 3%.

The only field with a relative discrepancy greater than 3% was the seventh. This was to be expected as it was the dose value closest to the working lower limit of the film. Nevertheless, the absolute discrepancy obtained is still small (0.24 Gy).

C. Comparision with other measuring devices

The measurements obtained from both the EBT-XD radiochromic films and the EPID were compared with the original treatment plan to determine the relative Gamma PR. The results, presented in Table III, show how the Gamma PR of the films is generally comparable to, or better than, that obtained with the EPID.

case	film (%)	EPID (%)
brain (SRS)	97.7	100
heart (SBRT)	99.3	90.2
lung (SBRT)	100	99.4

TABLE III: Relative Gamma PR of the different treatments considered. The columns represent:
1. Treatment case, 2. PR obtained with the film, 3. PR obtained with the EPID.

Moreover, as it can be seen in Fig. 4, the use of radiochromic films provides information of the dosimetry throughout the entire treated volume, as the film remains static in the irradiaton bed. This offers a more accurate representation of the actual radiation distribution, while the EPID image only provides this information in a single plane, as the device rotates along with the linear accelerator. Consequently, radiochromic films allow us to determine the specific anatomical areas where the dose calculation is inacurate, unlike the EPID image, where we cannot determine the clinical impact of the areas where the gamma analysis fails.

IV. CONCLUSIONS

We successfully characterized the EBT-XD radiochromic films for performing film dosimetry for SRS and SBRT treatments. We validated its ability to work within a higher dose range compared to EBT-4 films, verified the absence of significant polarization effects for the EBT-XD model, and validated the convenience of using the transmission scanning mode when working with high radiation doses.

We obtained a calibration set for the EBT-XD films that enabled us to work with different types of fields and film depths. To verify the calibration, seven field types with varying parameters were analyzed. The data obtained allowed us to confirm the validity of the chosen calibration set.

Finally, we tested the efficacy of the EBT-XD films by irradiating three treatment plans from different clinical cases: brain SRS, heart SBRT and lung SBRT. The relative Gamma PR was calculated for each treatment plan and compared with the results obtained using the EPID. The Gamma PR obtained with the films was not only improved or comparable to that of the EPID , but the images provided by the films also offered a more representative measure of the dose distribution across the entire planned target volume, allowing us to detect potential local failures in dose distribution.

The use of EBT-XD radiochromic films was deemed suitable for patient QA in highly modulated radiotherapy treatments and proved to be a convenient double-check alongside EPID imaging, helping to detect potential local issues with dose distribution in complex radiotherapy treatments.

Num.	Field size (cm×cm)	MLC (cm×cm)	Depth (cm)	SSD (cm)	D_d (Gy)	D_m (Gy)	σ (Gy)	d (Gy)	δ (%)
1	10×10	-	10	90	8.14	8.18	0.03	0.04	0.5
2	3.5×3.5	-	5	90	40.27	39.21	0.18	1.06	3
3	3.5×3.5	⌀ 2*	7	90	21.00	21.60	0.15	0.60	3
4	5×5	-	10	90	3.70	3.72	0.02	0.03	0.7
5	10 × 10	5×5	10	90	1.86	1.90	0.02	0.03	2
6	4×4	3×3	10	100	29.07	29.06	0.13	0.01	0.03
7	10×10	-	10	110	1.16	0.92	0.04	0.24	21

TABLE II: Lecture of the different conditions tested to validate the calibration. The columns show:
Parameters. 1. Film number, 2. Field size set by the jaws, 3. Field size set by the multileaf collimator (MLC) (- means no MLC applied), 4. Film depth, 5. Source to surface distance, 6. Delivered dose.
Measures. 7. Measured dose using EBT-XD films, 8. Standard deviation of the measured dose, 9. Absolute value of the difference between the delivered and measured doses, 10. Relative difference between delivered and measured dose.
*The shape is a circumference with a diameter of 2 cm.

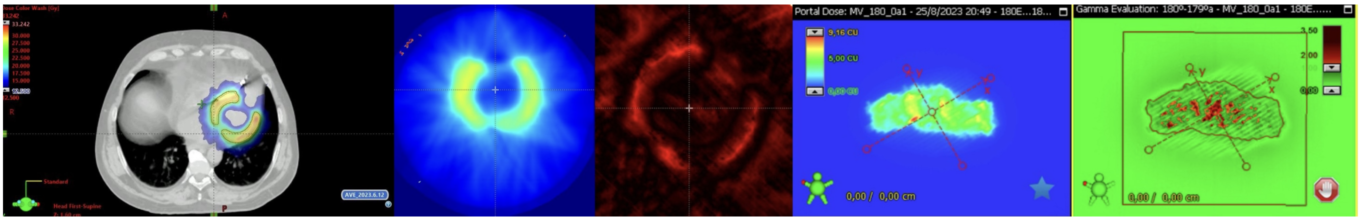

FIG. 4: Images of the heart SBRT patient dosimetry. From left to right the images show:
1. Dose distribution on the CT scan of the patient, 2. Dosimetry of the irradiated film, 3. Gamma analysis values of the irradiated film compared to the planned dose. Brighter values indicate gamma values closer to 1, 4. Treatment plan measurement in the EPID plane, 5. Gamma analysis distribution between EPID measurement and predicted treatment plan distribution at the EPID surface. Red areas indicate gamma values >1.

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Evaluació de l'ús de pel·lícules radiocròmiques EBT-XD per al control de qualitat específic en pacients per a tractaments de radioteràpia d'alta dosi

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Resum: Aquest treball avalua el comportament de les pel·lícules radiocròmiques model EBT-XD per al control de qualitat (QA) específic en pacients sotmesos a tractaments amb altes dosis de radiació. Tot i que aquests films són ideals per mesurar la distribució de dosi gràcies a la seva alta resolució i independència energètica, el seu ús presenta algunes incerteses associades al procés de manipulació i escaneig. L'objectiu d'aquest estudi ha estat caracteritzar paràmetres clau de les pel·lícules, com els efectes de polarització, les diferències entre modes d'escaneig i el rang de dosi de treball. Posteriorment, s'ha realitzat la calibració dels films i s'ha verificat la seva validesa mitjançant mesures en camps de dosi coneguda. Finalment, s'ha comparat la precisió de les pel·lícules EBT-XD amb la de l'electronic portal imaging device (EPID), utilitzant el gamma passing rate (PR) com a mètrica. Els resultats mostren que els films ofereixen un PR absolut superior al de l'EPID, a més d'una representació més detallada de la distribució de dosi, posant de manifest el seu potencial com a eina complementària en QA per a tractaments altament modulats.
Paraules clau: Física mèdica, acceleradors lineals, radiació ionitzant, interacció radiació-matèria.
ODSs: Aquest TFG està relacionat amb els Objectius de Desenvolupament Sostenible (SDGs)

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	
3. Salut i benestar	X	12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climàtica	
5. Igualtat de gènere		14. Vida submarina	
6. Aigua neta i sanejament		15. Vida terrestre	
7. Energia neta i sostenible		16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures	X		

GRAPHICAL ABSTRACT