Development of an experimental 3-D tool based on radiochromic films to determine normal tissue doses in external radiotherapy

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Abstract. External radiotherapy largely proved its efficacy to treat cancer. However, this technique leads to unavoidable exposure of normal tissues that may result in adverse effects. One of the main concerns is the induction of second cancers that may appear at the periphery or even away from the treated area. Risk estimation models need accurate 3-D dosimetric data on healthy organs. To this aim, we developed an experimental tool based on radiochromic films measurements. In this work, we present a study performed with a heterogeneous phantom. EBT3 films were positioned in between the phantom slices and irradiated according to a VMAT plan. The dose was reconstructed in 3-D by interpolation thanks to an in-house Matlab tool. Two interpolation methods are studied and the reconstructed dose is compared to independent film measurements for validation. Finally, dosimetric data such as DVH are compared to the TPS evaluation. Continuous interpolation proves to better reconstruct the doses in high gradient areas whereas linear interpolation seems to be a better option to evaluate doses away from the field edge. Besides, TPS and 3-D measurements give comparable results for organs placed inside the beams (maximum 6.3% difference on organs mean doses). However, the TPS tends to underestimate doses to organs placed at least partially outside the fields (from 29 to 59% difference on mean doses). Optimization of the dose reconstruction tool by using a combination of the two interpolation methods is ongoing. Comparison with gel dosimetry will also be investigated.

1. Introduction

External radiotherapy efficacy is widely acknowledged for its curative benefits to treat cancer. Therefore, this technique takes part in more than 50% of current treatments [1]. However, its most important drawback is the unavoidable exposure of healthy tissues to dose that may lead to secondary effects [2-3]. Some of those effects such as second cancers are stochastics and can appear at the periphery or even away from the treated target [1, 4]. The risk of second cancer induction raises a growing concern especially since modern techniques tend to irradiate a more important volume of tissues and since the better life expectancy of survivors increases the probability of second cancer appearance. Thus, evaluating the risk of adverse effects induction represents an important challenge. This estimation is based on risk models that correlate volumetric dosimetry and occurrence of adverse effects. Accurate 3-D dosimetric data inside and away from the treatment field are needed. For this purpose, the treatment
planning system (TPS) can only be used to evaluate in-field doses as its lack of precision for out-of-field dose evaluation is well documented in the literature [5]. Over the years, other techniques have been studied to estimate doses away from field edge: water or anthropomorphic phantom measurements and Monte-Carlo simulations. However, most of the experimental studies provide point measurements or unrealistic phantom geometries [6]. Within this context, we developed a new numerical tool on Matlab based on EBT3 films measurements to evaluate 3-D doses to normal tissues. The procedure consists in irradiating films placed in a sliced phantom. After a rigorous analysis of the films, 2-D dose distributions are interpolated to reconstruct the 3-D dose distribution. First, a preliminary study has been performed in a homogeneous phantom to evaluate the feasibility of the method. In this work, we present the results obtained with a heterogeneous configuration. The first part of this study is the validation and optimization of the tool. Finally, the reconstructed dose is compared to the evaluation of the Eclipse™ TPS (Varian Medical Systems) performed with two dose calculation algorithms: AAA and Acuros®.

2. Material and methods

2.1. EBT3 film calibration
In this study, EBT3 radiochromic films (Ashland) were prepared according to a rigorous protocol (cutting, calibration, readout) [7]. The irradiations were performed at the Institut Curie with a Clinac 2100CS linear accelerator (Varian Medical Systems), all the films were irradiated the same day. The films were calibrated from 1.35 cGy to 37 Gy with 24 points (2 films per dose) between tissue-equivalent slabs at 10 cm in depth with a 10×10 cm² field (SSD = 100 cm).

2.2. Phantom preparation
The EasyCube modular phantom (Euromechanics Medical) was used in this work in a heterogeneous configuration. The tissue-equivalent cube measuring 18 cm of side was filled with soft tissue, bone and lung inserts (Figure 1). Nine EBT3 films were cut to perfectly fit in the phantom (16×16 cm²), seven of them were spaced 2 from 2.5 cm apart in the phantom. The two leaving films were placed in between for validation (red arrows on Figure 1): one is dedicated to be placed at the target level and the other outside the beam path. The phantom was scanned (Siemens Definition AS OpenRT) with substitute films in place. A target volume of 3.5 cm diameter and the five heterogeneities were then contoured on the Eclipse™ TPS: the PTV is represented in orange on Figure 2, two lung volumes in blue and three bones in yellow. Two other organs were added in the soft tissue: the red organ is intended to be partially in the directly irradiated area (named OAR in this paper) whereas the brown volume is completely outside the beams (referred as OOF organ in this paper). A VMAT plan has been carried out on this geometry. 34 Gy was prescribed to the target volume in 17 fractions (one complete arc per fraction) for approximately 600 MU per fraction. The plan was calculated using two dose calculation algorithms available on the TPS: AAA (Analytical Anisotropic Algorithm) and Acuros®.
3.1 Validation of the reconstruction tool

First, the comparison between the intermediate film placed at the target level and the reconstructed dose allows to evaluate the tool precision on important dose gradient areas. In this case, the two interpolation methods used in the reconstruction underestimate the dose in the gradient. However, the continuous interpolation reproduces better the gradient shape (Figure 3). Away from the field edge, the linear method gives a better estimation of the dose in comparison with continuous interpolation. In both cases, the mean dose differences with the film measurement are around 24%, this value is representative of the discrepancies obtained in the gradient (from 90 to 110 mm on Figure 3).
However, when comparing the two interpolations with the intermediate film placed away from the beams, the linear interpolation proves to be the best option (Figure 4). The mean dose difference between reconstructed dose with linear interpolation on this slice and the intermediate film is of 7.0% against 9.4% for the continuous interpolation and 95.5% of the points pass the 10% / 3 mm gamma test against 87.6%. The agreement between intermediate film measurement and interpolations is much better than the comparison with the TPS evaluation. In fact, the mean dose difference is of 30.2% when comparing the AAA dose distribution to the film (13.1% of points passing the 10% / 3 mm gamma test) and 35.2% when comparing the Acuros® slice (2.8% of points passing the 10% / 3 mm gamma test). Figure 5, representing a perpendicular dose profile, shows that continuous interpolation better reconstructs the gradient shape. Thus, this technique allows to slightly reduce the reconstruction errors in this area.
3.2. Normal tissue doses evaluation
Doses delivered to contoured organs are compared between reconstructed dose (with the two interpolations) and TPS. Table 1 summarizes dose difference between mean organ doses. The tool underestimates doses to the PTV as high gradient cannot be perfectly reproduced. Linear interpolation overestimates doses to the three bones, which are placed in the gradient between in-field and out-of-field areas. For the other organs the difference between the two interpolation methods are small. AAA and Acuros® give similar results for the PTV and for organs placed inside the beams (maximum difference in mean organ doses 6.3%), but for organs placed outside the field Acuros® underestimates organ doses by up to 17% compared to AAA. Finally, the TPS (both AAA and Acuros®) largely underestimates the doses delivered to out-of-field organs (from 29% for the OAR to 59%) compared to the reconstructed dose. Figure 6 represents the DVH obtained with the experimental tool (two interpolation methods) and with the TPS AAA algorithm.

Table 1. Difference between mean organ doses obtained with the reconstructed film doses and the TPS.

| Organs       | Difference between mean organ doses (%) |
|--------------|-----------------------------------------|
|              | Linear / continuous interpolation | Linear interpolation / AAA | Continuous interpolation / AAA |
| PTV          | -2.3                                    | -7.3                       | -4.8                          |
| OOF organ    | 3.6                                     | 37                         | 35                            |
| OAR          | 6.3                                     | 29                         | 25                            |
| Bones        | From 15% to 29%                         | From 52% to 59%            | From 43% to 47%               |
| Lung (in-field) | 2.0                                      | -1.1                       | -2.4                          |
| Lung (out-of-field) | 1.3                                     | 24                         | 22                            |
4. Discussion

4.1. Validation of the reconstruction tool

Results obtained when comparing reconstructed dose distribution and intermediate film measurements show that our method can be used to evaluate out-of-field doses or doses in low doses areas within the field. In fact, the reconstructed dose proves to be more accurate than the TPS away from the field edge (see 3.1.). Linear interpolation seems to better reproduce the dose evolution away from the target (Figure 2 and 3). However, even though continuous interpolation reduces errors in high gradients, they cannot be precisely reconstructed. A combination of the two interpolation methods seems to be a good alternative.

4.2. Normal tissue doses evaluation

The TPS normal tissue doses underestimation observed in our work is consistent with the results of the literature [6-8]. This is mainly due to head scatter and head leakage that are not modelled in the TPS, in fact this radiation contributes to more than 40% of the out-of-field dose: Joosten et al. [5] report that TPS and Monte-Carlo simulation show major discrepancies, even for organs located near the treated area, that can reach 70%. In this work, the dose reconstruction tool was used in a narrow volume, but it enables dose determination for organs away from the target even in area where TPS doses are often not calculated (outside the scanned volume).

5. Conclusion

In this work, we present an original in-house tool that enable to obtain reconstructed 3-D doses to normal tissues by experimental means. This tool developed on Matlab and based on radiochromic films has been validated against film measurements and the reconstructed doses compared to the TPS evaluation. The results show major TPS underestimations of the out-of-field doses. In order to improve the accuracy of the developed tool, a combination of linear and continuous shape-preservative interpolations is currently investigated. Finally, a comparison with 3-D gel dosimetry is also considered. This tool will be used in future work to estimate normal tissue doses delivered by advanced radiotherapy techniques on paediatric anthropomorphic phantoms.

6. References

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