Head and Neck Immobilization Masks: Increase in Dose Surface Evaluated by EBT3, TLD-100 and PBC Method

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Abstract
Positioning and immobilization tools are considered essential components of radiotherapy treatments to guarantee that the planned dose distribution can be efficiently reached. However, the benefits brought by their use are met by an apparent increase in the patient skin entrance dose. In the current study, we evaluated the dose surface effects provoked by the use of immobilization thermoplastic masks in head and neck radiotherapy treatments, carried out using a 6-MV linear accelerator beam. The study was carried out using an anthropomorphic head–neck phantom and three dosimetric techniques: (i) thermoluminescent dosimetry (TL); (ii) radiochromic film dosimetry; and (iii) computational simulation using the pencil beam convolution (PBC) method. For calibration purposes, TLD chips and radiochromic (EBT3) small 2.0-cm² strip dosimeters were positioned between two virtual solid water plates, and exposed to absorbed doses ranging from 25 to 200 cGy. The use of an anthropomorphic head–neck phantom allows the dose variation in non-flat surfaces to be taken into account. TLD chips, positioned on the surface of the supraclavicular fossa anatomical region, covered with a thermoplastic mask, detected an entrance skin dose that was approximately 38.4% higher than that measured without a mask. The EBT3 dosimeters, averaged among all strips used, also detected a medium increase of 58.6%. Both TLD and EBT3 detected increased doses for all measured points, and measured similar averaged surface doses without the use of immobilization masks; that is, 50.5% for EBT3 and 53.7% for TLD-100. The pencil beam convolution simulation results suggested an increase for most of the measured points; however, no increased, and in some cases even decreased, doses were observed. The surface dose data of three other commercial thermoplastic masks irradiated in a solid water phantom are also provided.

KEYWORDS
EBT3 films, radiotherapy masks, skin sparing, surface dose, thermoluminescent dosimetry, thermoplastic masks
1 | INTRODUCTION

High-energy clinical beams provide an immediate benefit for the treatment of malignant diseases, and consist simply of low-radiation dose distribution along the patient’s skin surface. In fact, in the dose distribution versus the tissue depth curves, an electronic disequilibrium region exists, which is usually larger than the average skin thickness. This results in an advantage over preservation of this sensitive tissue, and an effect that is commonly reported in the literature as skin sparing.1-3

Regardless of this benefit, the use of immobilization tools, such as thermoplastic masks and molds, both of which are used for patient positioning and immobilization, has led to a reduction in the use of skin sparing in radiotherapy procedures. For instance, Lee et al.4 measured an average 18% increase in the surface dose caused by thermoplastic masks used for intensity-modulated radiotherapy treatments, whereas Higgins et al.5 measured the increase in the surface doses caused by carbon fiber tables to be as much as 400%. Thus, as a consequence of this increase in surface dose, the correct evaluation of the dose superficialization effect becomes very important.6 In clinical practice, the effect of dose superficialization in radiotherapy treatments confronts the benefits brought by the use of immobilization materials. Despite this problem, immobilization tools are considered essential to guarantee the reproducibility of the patient positioning and immobilization during the entire period of treatment, and therefore ensuring that the planned dose distribution can be efficiently reached in the final phase of treatment. In this context, it is important to evaluate the usefulness of these immobilization devices, considering the damage provoked by the radiation dose increase in shallow skin regions. Using mega-voltage X-ray beams, Hadley et al. tested a mask with larger holes for head and neck immobilization on the surface of a solid water phantom.5 They measured an increase in surface dose by a factor of at least 50% in the best conditions. In contrast, using a 6-MV linear accelerator beam, Ali et al. studied these effects using Gafchomric EBT films over a flat surface phantom.7 Furthermore, Kelly et al.8 measured these effects over a rigid anthropomorphic breast phantom, also using EBT film. Both studies confirmed an increase in the surface radiation dose.

In the current study, we examined the dose surface effects provoked by the use of immobilization thermoplastic masks for head and neck radiotherapy treatments, performed with a 6-MV linear accelerator beam. According to the American Association of Physicists in Medicine Task Group 176 report recommendations, which provides a comprehensive review of the dosimetric effects caused by couch tops and immobilization devices, characteristics such as dose range, spatial resolution, accuracy, and angular dependence, should be considered when choosing a detector for a specific measurement of surface dose and build-up.9 Furthermore, large dose gradients and electronic disequilibrium near the surface require dosimeters to have a well-defined and small volume, in addition to an output response that is independent of the electron energy. In this context, the most common detectors used for the measurement of build-up and surface dose are extrapolation chambers, plane parallel chambers, thermoluminescent dosimeters (TLD), and film. Thus, in the present study, to accurately measure the delivered dose to the skin of the head and neck during a typical radiotherapy treatment, we used an Alderson Rando anthropomorphic head–neck phantom submitted to rigorous 3-D radiotherapy planning and two dosimetric techniques: thermoluminescent dosimetry (TLD-100) and radiochromic film dosimetry (EBT3). For the purpose of comparison, we also utilized used another technique, the pencil beam convolution (PBC) computational simulation method. We believe that this methodology allows for the dose variation in non-flat surfaces to be taken into account, as well as the dose comparison among three different dosimetric systems, thereby providing a more realistic dose surface evaluation.

2 | METHODS

2.1 | Treatment planning in the anthropomorphic phantom

An Alderson Rando anthropomorphic phantom was utilized to reproduce radiotherapy treatments in the head and neck regions. The phantom was submitted to rigorous 3-D radiotherapy planning, and the daily dose delivery parameters were obtained through computational calculations. Computed tomography was used to perform the usual 3-D planning of the radiotherapy treatment. The Alderson Rando was positioned according to the treatment protocol for head and neck patients. Computed tomography was performed with and without the presence of a thermoplastic mask over the simulator. Small acrylic spheres were glued on the surface before computed tomography scanning to facilitate precise visualization of the points on the simulator skin. The points were carefully selected to provide the correct evaluation of the dose superficialization effect in various cervico-facial tissue regions. A fictitious tumor occurring next to the base of the tong was considered in order to justify the adoption of a radiotherapy treatment that uses the application of three daily fields. The treatment was calculated using a 3-D conformal method. The lesion treatment in the supraclavicular fossa (SCF) was established using a field guided directly to this region, with a gantry of 0°. The dose prescription point was established at a 2-cm depth in the center of the lesion region. The thermoplastic mask and head support, appropriated for the anatomical dimensions of the simulator, were prepared in accordance with international therapeutic protocols. The treatment was performed in a 6-MV Linear Electron Accelerator Clinac 2100C (Varian Medical Systems, Palo Alto, CA, USA) in a 10 × 10-cm² field.

2.2 | Dosimetric instruments

The main goal of the current study was to provide a more realistic dose surface evaluation by using a methodology that allows the dose variation in non-flat surfaces to be considered based on dose comparisons among three different dosimetric systems. In this context, radiochromic films have been extensively used for dosimetry in radiation medicine in recent years.10,11 They have several advantages when
thin adhesive tape was used to fix the film pieces on the surface, as seen in Figure 2. A set of TLD-100 chips, previously calibrated at the same condition as the EBT3 film (i.e., under virtual solid water plates) were placed between the adhesive tape and the radiochromic film, exactly above the previously mapped points. This methodology was used to perform phantom irradiation with and without the thermoplastic mask. The PBC dose evaluation was also performed under these two conditions.

A group of 170 commercial LiF:Mg,Ti (TLD-100) chips were pre-selected from a larger group by exposing the examined samples to 100 mGy of gamma rays, with photon energies of 662 keV, from a $^{137}$Cs gamma source at room temperature. This process was repeated three times to determine the individual correction factor for each chip. The chips with a thermoluminescence (TL) response $>4.0\%$ were discarded. No fading correction factors were applied, because the TL readings were collected just after the irradiation process. No energy correction factors were used once the TL over-response for TLD-100 was just 1.3 below 100 keV, and 1.0 above 100 keV. The TL Output x Dose experimental data was better peak-fitted by a second-order polynomial function with $R^2 = 0.99949$, as shown in Figure 2. The measurements of TL glow curves were performed using a Harshaw-Bicron 3500 TLD reader (Thermo Fisher Scientific, Waltham, MA, USA), operating under a linear temperature profile over the range of 50–300°C, in the resistive mode, using a heating rate of 10°C/s and reading cycles of 35 s. Annealing was performed at 400°C (1 h) and 100°C (2 h) before irradiation. Pre-reading annealing was carried out by heating at 100°C for 15 min. In the generation of the TLD calibration curve, the top 4.0 cm of virtual solid water in Figure 1 was changed to another with 1.0 cm, to compensate for the 0.4 mm of acrylic that was placed in each side of the TLD holder.

The PBC algorithm used in the present study was a dose calculation analytical method used by the Varian Medial Systems for radiotherapy planning. The most modern calculation algorithms implemented in treatment planning systems (TPS) are the pencil beam and super-position/convolution techniques, such as the collapsed cone. The collapsed cone algorithm implements various approximations in the physics of radiation transport, which reduces the calculation time to...
levels that are acceptable for clinical practice. Although the pencil beam algorithm is very fast, the limitations in heterogeneous media are well known. This is because the pencil beam uses a one-dimensional density correction that does not accurately model the distribution of secondary electrons in media of different densities.\textsuperscript{15}

3 | RESULTS

3.1 | Dose evaluation using TLD chips

A total of 12 TLD chips were positioned on the surface of the SCF anatomical region to measure the skin dose variation in radiotherapy procedures performed with and without the use of a thermoplastic mask (Figure 3). The setups were submitted to an anterior/posterior irradiation procedure, in agreement with the approved radiotherapy planning for head and neck radiotherapy treatments.

The measured skin doses after the irradiation procedure, for each chip position in the anthropomorphic phantom, are shown in Figure 3. The planned delivered doses were 180 cGy for both procedures. The doses recorded by the TLD-100 chips show a higher superficial dose deposition for the treatment performed with the use of the thermoplastic immobilizer, because every measuring point over the slices F, E, and C recorded increased doses. The surface dose was estimated to change from 53.7\% of the 180 cGy delivered dose (with no mask) to 72.9\% (with mask), resulting in a dose increase of 38.4\% averaged over the SCF region. The surface dose evaluation included measurements in the build-up region, the region of electronic imbalance. In addition, the

\textbf{FIGURE 2}  Schematic diagram showing the thermoluminescent dosimetry calibration setup using virtual solid water. EBT3 radiochromic films and TLD-100 chips placed over the skin’s anthropomorphic phantom, covering all mapped points of interest in an Alderson Rando anthropomorphic phantom. (a) This setup is covered by a thermoplastic mask. (b) TL Output x Dose experimental data peak-fitted by a second-order polynomial function

\textbf{FIGURE 3}  Superficial dose deposition in the supraclavicular fossa anatomical region measured by TLD-100 dosimeters after exposure to 180 cGy, with and without a thermoplastic immobilizer. F, E, and C indicate the slices over the phantom, each of which contains thermoluminescent dosimetry (TLD) chips
3.2 Dose evaluation using radiochromic films

Small 2.0-cm² EBT3 film pieces were placed at the same measuring points used to perform TLD-100 measurements; that is, over the slices E and C in the SCF region, to compare the two dosimetric systems responses (Figure 4). The results of the irradiation performed without an immobilization mask are shown in Figure 4a, whereas the corresponding results related to the irradiation performed with the mask are shown in Figure 4b.

By considering the previous information recorded by TLD-100 (Figure 3), it is possible to observe an agreement between the two dosimetric systems after both systems showed an increase in surface dose at all slices. The surface dose was estimated to change from 50.5% of the delivered dose (with no mask) to 79.8% (with mask), resulting in a dose increase of 58.6% averaged over the SCF region. This dose increase measured by EBT3 films was higher than that measured by TLD-100 (i.e. 38.4%), but is still underestimated when compared with the increase measured by Scott et al., which was >100%. An increase in the dose surface from 90–100 cGy to 130–150 cGy was observed by the EBT3 film, against the 90–100 cGy to 120–140 cGy evaluated by TLD-100. The well-known high spatial EBT3 film resolution provides additional information regarding the limit between the high-dose region (>90 cGy) and the low-dose region (20 cGy), which is attributed to the secondary collimator in the linear accelerator head. In addition, the EBT3 films showed an unexpected increase in the surface dose in the right upper side (~150 cGy) when compared with the right side (~120–140 cGy), which was provoked by the thermoplastic mask.

According to the data provided by both the TLD and EBT3 dosimetric systems, shown in Figures 4 and 5, respectively, it was possible to verify an increase in the entrance skin dose due to the use of the immobilization mask. In particular, all SCF regions covered by the EBT3 film strips registered an expressive dose increase in the superficial layers (Table 1). The greatest increase was observed at strip number 17, which recorded a median increase of 72.90 cGy; that is, an additional superficial dose of 104%. Taking into account that the medical prescription dose was 180 cGy, the EBT3 data averaged among all strips resulted in a medium increase of 70%, originated by the presence of the immobilization mask during the treatment.

For comparison purposes, we extended the study to include additional mask materials, and a different surface for irradiation, the solid water phantom. The commercial masks used in this irradiation were as follows:

1. Mask 1: Medintec M14 – batch M1611684
2. Mask 2: Ofix Curve RT – 1892YESD Aquaplast
3. Mask 3: RG 461 – 4VT Accu Perf

The surface doses measured under the influence of these masks (under the mesh and also under the hole of each mask) were evaluated using EBT3 films. All experiments were performed with the same setup: The radiation field was $10 \times 10 \text{ cm}^2$ at 100 cm from the source, and the delivered dose was 200 cGy at 5 cm in the solid water phantom. The dose surfaces are shown in Table 2. The results show that the doses measured under the mesh were higher than those measured over the mask and those measured under the holes, for all three masks studied. The surface doses measured without the mask were considerably smaller. For a delivered dose of 200 cGy, the RG 461 mask increased the skin dose of 28.1 cGy (without mask) to 197.9 cGy (under the mesh). By comparing the doses under the mesh with the doses under the holes,
TABLE 1  Median dose and associated error measured by EBT3 film strip numbers 20, 21, 22, 23, 24, and 25 positioned over the supraclavicular fossa

| Treatment performed | Strip 16 | Strip 17 | Strip 18 | Strip 20 | Strip 21 | Strip 22 | Strip 23 | Strip 24 | Strip 25 |
|---------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| With mask           | 125.77   | 142.61   | 134.4    | 123.35   | 138.79   | 141.19   | 119.07   | 124.80   | 133.85   |
| Error (cGy)         | 6.3      | 7.1      | 6.7      | 6.17     | 6.94     | 7.06     | 5.95     | 6.24     | 6.70     |
| Without mask        | 92.69    | 69.71    | 90.46    | 83.11    | 72.02    | 80.49    | 70.35    | 68.43    | 88.27    |
| Error (cGy)         | 4.63     | 3.49     | 4.52     | 4.16     | 3.60     | 4.02     | 3.52     | 3.42     | 4.41     |

The medical prescription dose was 180 cGy.

TABLE 2  Surface dose under the influence of a thermoplastic mask, evaluated under the mesh and also under the hole of each mask

| Surface dose under the influence of the thermoplastic mask | Medintec M14 | Ofix curve RT | RG 461 | Without mask |
|----------------------------------------------------------|--------------|---------------|--------|--------------|
| Average dose                                             | 164.6 cGy    | 167.3 cGy     | 186.9 cGy | 28.1 cGy     |
| Dose under the mesh                                       | 186.9 cGy    | 191.2 cGy     | 197.9 cGy |              |
| Dose under the hole                                       | 134.0 cGy    | 135.4 cGy     | 136.0 cGy |

The delivered dose was 200 cGy at 5 cm in the solid water phantom.

for all masks, the last is quite smaller, leading us to conclude the masks with higher holes; that is, with less mesh, might provide reduced doses to the patient’s skin.

3.3  Dose evaluation using PBC

The results of the PBC dose calculation analytical method dose evaluation, simulating an exposure of 180 cGy, with and without thermoplastic immobilizer are shown in Figure 5. The results suggest an important increase in the superficial dose when using immobilization masks, for the majority of the measured points. Although these results are in agreement with the previous results obtained using TLD chips and EBT3 film dosimeters, the results obtained at position E11 and C16, unlike the other two dosimetric systems, show reduced doses with the use of a thermoplastic mask. Furthermore, the overall entrance skin doses evaluated by the PBC method with immobilization masks were 50% smaller than those measured by TLD-100 and EBT3.

4  DISCUSSION

Thermoplastic masks used for patient positioning and immobilization have led to a reduction in the use of skin sparing in radiotherapy procedures, although they contribute to a notable increase in the skin radiation dose. The magnitude of this phenomenon, and its consequent clinical influence, will depend on the characteristics of the immobilizer material, such as the thickness, as well as the characteristics of the incident beam, such as energy spectrum and obliquity. The dose surface effects measured in the present study, provoked by the use of immobilization thermoplastic masks for head and neck radiotherapy treatments, also show an incontestable increase in the dose of radiation to the skin. This increase was detected by all three dosimetric systems utilized (TL dosimeters, EBT3 radiochromic films, and PBC), although the PBC system has evaluated it, with small differences in comparison with the other two systems.

TLD-100 and EBT3 films have shown discrepancies in increasing dose surfaces, 38.4% and 79.8%, respectively, when the immobilization mask is placed in the Rando phantom. Indeed, Scott et al. tested an immobilization mask with small and large holes for head and neck irradiation procedures on the surface of a solid water phantom in a LINAC EX21. They used an Attix parallel plate chamber to perform the measurements normalized to 15-mm depth. The surface dose was estimated to change from 16% of the delivered dose (with no mask) to 31% and 35% (with mask extended 300%) for small and large holes, respectively, exposed to 6-MV photo beams, resulting in a dose increase > 100%. Thus, the increase in dose surface values registered using TLD-100 over the anthropomorphic phantom is underestimated when compared with data reported by these authors. This result is expected, as the TL dosimeters used in the present study measure the average dose over the most superficial thickness, which might lead TLD-100 to underestimate the increase in dose. The measurements made with the Attix chamber were normalized at a depth of 15 mm, and the surface dose evaluation included measurements in the build-up region, the region of electronic imbalance. In addition, the TPS used to calculate the surface doses in the present work has low accuracy in the build-up region, which justifies the discrepancy between the TLD results and the dose determined by TPS.

Both dosimetric systems measured similar averaged surface doses without the presence of immobilization masks; that is, 50.5% for EBT3 and 53.7% for TLD-100. It is well-known that commercial Harshaw TLD-100 chips, 0.9-mm thick, overestimate surface doses, and that
the Extra-Thin TLDs and Black TLDs perform better in this type of dosimetry. For instance, Kron et al. irradiated TLD-100 0.9-mm thick in a similar Linear Accelerator (Clinac 2100) under the same conditions (10 × 10 cm²) in a solid water phantom, and showed that the dose surface was overestimated by a factor of 2.61. Thus, if a correction factor close to this is applied to our TLD-100 results, the range of surface doses measured would be 20.5%, which is in agreement with the values encountered by Extra Thin (20.8%) and Black TLDs (19.4%) irradiated under the same conditions. Interestingly, this result correction of TLD-100 opens a new question regarding the dose surface evaluated by EBT3 films, which, in this case, would be overestimated; that is, 50.5%. We note that this value was averaged over the surface dose measured by EBT3 films over exactly the same TLD-100 chip positions (F10–F21, E5–E11, and C4–C16). If we take the surface dose averaged over the tapes 16–25 (data in Table 1 and Figure 4), the mean dose is slightly smaller, at 44.1%. In a similar study, Akbas et al. reported the surface dose, with EBT3 films in a water equivalent RW3 slab phantom, to be 20.4% of the applied dose. Thus, in the future, some improvements should be made to the calibration procedures of EBT3 films to decrease the overestimated values found in the present study.

The entrance skin doses evaluated by the PBC method without the presence of immobilization masks were smaller than those measured by TLD-100 and EBT3. Just three measurements (F10, E11, and E17) were in the range of 60–80 cGy, whereas at the remaining nine points, all measurements were <30 cGy. The PBC simulation results suggested an increase for most of the measured points, although, no increased, and even decreased, doses were obtained. The dose calculation algorithm used elsewhere for radiotherapy procedures, known as PBC, is an important Monte Carlo code-based analytical method. In the present study, we carried out computational evaluation of the dose delivered to the anthropomorphic phantom surface in an attempt to determine its accuracy when compared with two other dosimetric systems. However, PBC, although largely cited in the literature, might also present significant failures, mainly with respect to dose evaluation performed in small field treatments, as well as for distribution dose evaluation in electronic disequilibrium regions. The dosimetric uncertainties observed in these regions, for instance, in the interface between tissues of different densities, is somehow accepted by the international organizations that publish radiotherapy protocols. One such example is the Task Group 53 American Association of Physicists in Medicine recommendation that has established 40% as the uncertainty limit in the build-up regions. Nevertheless, hospitals and clinics worldwide make use of software that provides TPS based on the PBC method.

Finally, although this study has discussed the increase in skin radiation dose that arises with the use of thermoplastic immobilizers, it is fair to consider that the immobilization instrument is an essential tool for the success of radiotherapy treatment by ensuring the reproducibility of the patient positioning. Without the immobilizer, the skin damage would be significantly worse than the dose superficialization effect. Thus, it is reasonable to suggest that the development of new immobilization devices, that can maintain the benefits of the immobilization and simultaneously barely contribute to the dose superficialization in the patient, should be encouraged.

TLD-100, EBT3, and the PBC method have been used to evaluate the increase in surface radiation dose provoked by immobilization masks in head and neck radiotherapy procedures. After irradiation with 180 cGy in the Clinac Linear Accelerator model 2100C at 6 MV, TLD chips positioned on the surface of the SCF anatomical region of an anthropomorphic phantom covered with a thermoplastic mask detected an increase in the entrance skin dose of approximately 38.4%. The data from the small EBT3 2.0-cm² strips, averaged among all strips used, also detected a medium increase of 58.6%. Both dosimetric systems have measured similar averaged surface doses without the presence of immobilization masks; that is, 50.5% for EBT3 and 53.7% for TLD-100. The well-known high spatial EBT3 film resolution provides additional information regarding the limit between the high dose region (>90 cGy) and the low-dose region (20 cGy), which is attributed to the secondary collimator in the linear accelerator head. In contrast to PBC evaluation, both TLD and EBT3 detected increased doses for all measured points.

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