**In vivo and phantom measurements versus Eclipse TPS prediction of near surface dose for SBRT treatments**

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**Abstract.** This study reports on Gafchromic EBT2 film skin dose measurements for lung stereotactic body radiotherapy. These measurements were compared to near surface skin doses predicted by Eclipse treatment planning system (TPS) using the Analytical Anisotropic Algorithm (AAA) for a 6 MV photon beam. The accuracy of the predicted near surface dose for 3×3, 5×5 and 10×10 cm\(^2\) fields was assessed using an Attix chamber and EBT2 film in a Virtual Water phantom and compared to Monte Carlo calculation. The maximum near surface dose and its location were identified from the patient’s treatment plan. For phantom measurements, the TPS dose (nominal 0 mm depth) was higher than the Attix chamber data by up to 24.0 % but in closer agreement with the EBT2 film measurement, which was up to 10.3 % higher than the Attix data. The MC calculated dose values were higher than the Attix data by up to 3.5% for the depths up to 2 mm. The maximum patient skin dose estimated from in vivo EBT2 film measurements was 7.5 – 19.5 Gy per course and depended on the number of overlapping fields, beam weight and/or contact with immobilisation devices. The TPS predicted dose for patient plans was mostly higher than the in vivo dose, by as much as 69.3%, but in two cases was lower, by as much as -23.1%.

1. **Introduction**

For patients undergoing stereotactic body radiotherapy (SBRT), also known as stereotactic ablative body radiotherapy (SABR), the skin is one of the critical organs at risk that requires dose monitoring due to the use of potentially overlapping multiple treatment fields in conjunction with highly hypofractionated dose prescription scheme [1, 2].

The estimation of the skin dose received from a megavoltage (MV) photon treatment requires specific dosimetric considerations due to the lack of charged particle equilibrium present in the build-up region. In this study, we refer to the clinically relevant nominal skin depth as 70 \(\mu\)m based on ICRP definitions [3]. The dose to patient’s skin may be altered by build-up effects, dose from beams exiting the patient and/or scatter from the immobilization devices or beam modifiers required for patient set-up and treatment [1, 4, 5].

A patient’s treatment plan from a TPS provides a calculated dose given to the target. However, the accuracy of the dose prediction by a TPS in the build-up region is reduced leading to broader tolerance limits [6, 7]. Several factors influence the TPS near surface dose prediction: dose calculation algorithm...
and its electron contamination model, initial commissioning of TPS build-up region dose calculation, clinical dose calculation parameters and treatment plan complexity [8].

Eclipse™ analytical anisotropic algorithm (AAA, V10.0.29, Varian Medical Systems Inc, Palo Alto, CA) uses triple source models comprised of primary photons, extra-focal photons and contaminating electrons to approximate the phase space parameters (particle fluence, energy spectrum) of the clinical beam. During the configuration step, the physical parameters that model each source are optimized using measured beam data. For volumetric dose calculation, the clinical beam is represented by 2-D fluence distributions comprised of photon and contaminating electrons that are divided into small beamlets. A 3-D matrix of calculation voxels, each with an associated mean electron density, and the voxel resolution determined by the dimension of calculation grid is formed from the patient body volume. The energy distribution is obtained from separate convolutions for two photon sources and electron contamination source. The dose at a calculation point is obtained by summing up the individual beamlet contributions by global superposition and finally converting absorbed energy to dose by dividing by the local (relative) electron density.

The fluence of contaminating electrons is obtained by convolving the primary photon fluence with a Gaussian (target plane) and the dose deposition by these contaminating electrons is calculated by the convolution with a second Gaussian, multiplied by the depth dependent energy deposition function. An empirical curve determined from the difference between the measured depth dose and the dose calculated by AAA without contribution from contaminating electrons for the largest field size (open beam), models the total energy deposition. More accurate modeling of electron contamination could contribute to improved accuracy of field size dependent build-up region dose prediction [9].

For typical SBRT treatment field arrangements, the limited accuracy in the TPS entrance dose prediction could add further uncertainty to the estimated skin dose where entry beam(s) may overlap with exit beam(s) and additional build-up effect and/or scatter arises from the presence of immobilization devices [10].

In this study, near surface doses were calculated by the AAA for a 6 MV photon beam and compared with measurements using an Attix parallel plate chamber and Gafchromic EBT2 film (International Specialty Products, Wayne, NJ). These results were also compared to Monte Carlo (MC) calculations using BEAMnrc/EGSnrc. We also report on EBT2 film in vivo doses for nine lung SBRT treatments and compare with Eclipse™ dose predictions.

2. Materials and methods

2.1. Eclipse™ phantom dose calculations
For a 6 MV photon beam, the dose calculation was performed on an Eclipse™ water phantom at a 100 cm source to surface distance (SSD) for 3×3, 5×5 and 10×10 cm² field sizes at two gantry angles (0° and 30°). For dose calculations, a constant 100 monitor unit (MU) was prescribed and routine clinical AAA calculation parameters were used (calculation grid size 0.25×0.25×0.25 cm³ and heterogeneity correction on). Point doses were extracted at depths of 0, 2, 4 and 6 mm along the central axis.

2.2. Attix chamber and EBT2 film phantom dose measurements
Surface dose measurements were performed using an Attix parallel plate chamber and EBT2 films in a Virtual Water™ (Med-Cal, Verona, WI) phantom using a Novalis Tx linear accelerator (Varian Medical Systems Inc, Palo Alto, CA). The reference point of an Attix chamber is located at a water equivalent depth of 48 μm being the inner surface of the chamber entrance window, which is less than the ICRP skin depth of 70 μm. For dose conversion, reference output measurements for the Attix chamber were performed in Virtual Water™ at 100 cm SSD for 10×10 cm² field size and at the depth of dose maximum (1.4 cm) and with 100 MU. The electrometer (PTW Unidos, Freiburg) readings were taken for two bias voltages with the chamber positioned at depths of 0, 2, 4 and 6 mm at the central axis while maintaining a fixed 100 cm SSD to the phantom surface. A total of six readings from both polarity settings (-300V and +300V)
were averaged and converted to dose prior to normalisation at the depth of 1.4 cm. The chamber readings were not corrected by water-air stopping power ratios.

The cross section of EBT2 film is asymmetric, with the 30 µm thick active layer starting at a physical depth of 80 µm. For dose conversion, EBT2 films were calibrated at 1 Gy intervals up to maximum dose of 6 Gy with the 80 µm side facing the X-ray source. The same reference set-up in section 2.2.1 for the Attix chamber was used. EBT2 film depth dose measurement was performed at two gantry angles and at four depths as described in section 2.2.1, with each film piece placed on the central axis. The films were irradiated individually at 300 MUs.

2.3. Eclipse skin dose estimation and in vivo skin dose monitoring using EBT2 films

The clinical SBRT protocol utilizes a maximum dose limit of 30 Gy to the chest wall and skin based on the TROG 0902 clinical trial protocol recommendations [11]. A 5 mm thick inwardly expanding artificial skin structure was generated as part of contouring to estimate the maximum near surface skin dose via the dose volume histogram (DVH) statistics [2]. The reported DVH maximum dose was used as a conservative upper estimate of the near surface skin dose. Where the maximum DVH dose was found, the overlying near surface dose was evaluated for comparison with the in vivo film measurement. In addition, the overall dose distribution was evaluated using the Eclipse™ dose colour wash tool. Multiple overlap regions from entry and the exit beams and resulting high dose regions were also identified for film positioning and evaluation. The skin dose from Eclipse patient plan was recorded at a point closest to the skin and less than 2.5 mm distance inward from the surface, assuming a coverage by one calculation voxel. For patient skin dose estimation, calibration was performed for each individual sheet of in vivo EBT2 films up to 8 Gy prior to patient measurement. On the first day of treatment, in vivo dose measurements were performed using EBT2 films if the skin DVH maximum dose was greater than 20 Gy or for audit. In vivo EBT2 films were marked consistently to identify the film orientation for positioning and scanning.

2.4. EBT2 film scanning and dose evaluation

All EBT2 films were scanned approximately after 18-24 hours using an Epson 10000XL flatbed scanner. The films were scanned in a landscape orientation at the scanning resolution of 72dpi and in 48bits RGB format. The scanned film images were imported into RIT113 software (Radiological Imaging Technology Inc, Colorado Springs, CO) using the red channel. Calibration curves were generated and the pixel values of the films were converted to absorbed dose. The converted dose was sampled using a region of interest (ROI) dimension set to 7×7 mm² at the centre of each film pieces.

2.5. Monte Carlo simulation

The MC calculation was performed for 3×3, 5×5 and 10×10 cm² field sizes using the BEAMnrc/DOSXYZnrc Monte Carlo (MC) code. The first step involved generating the phase space file for the linear accelerator using BEAMnrc. In this simulation, a total of 8×10⁷ incident electrons of 6.5 MeV energy specified as an elliptical beam with varying FWHM depending on the field size. The EGSnrc transport parameters ECUT/PCUT were set to 0.521 and 0.010 MeV and AE/AP were set to 0.512 and 0.001 MeV. Directional bremsstrahlung splitting was turned on with a splitting factor of 1000 and the XCOM photon cross section and NIST bremsstrahlung cross-section data were used. Boundary crossing algorithm was set to EXACT and for electron step algorithm, PRESTA-II was used. For surface dose calculation, a total of 8×10⁹ particle histories were used incident upon a large water phantom. The dose in water was scored in voxels with 10 µm in thickness and 0.5 cm in radius for the first 0.1 mm in a water phantom that includes the relevant skin depth (70 µm) [12, 13].

3. Results and discussion

3.1. Comparison between phantom measurements and the Eclipse AAA predicted dose
Table 1 and 2 show the comparison between the Attix chamber, EBT2 film measurements and AAA predicted doses at two gantry angles 0° and 30°, respectively. The results show that AAA consistently overestimates the surface dose (nominal 0 mm depth) compared to the measured data (Attix and EBT2). In contrast, at 4 and 6 mm depths where maximum skin DVH dose is estimated, Eclipse AAA underestimates the dose. At the phantom surface and gantry angle 0°, the EBT2 film dose was consistently higher than that of the Attix chamber.

Table 1. Phantom measurements for gantry angle 0°. Attix chamber and EBT2 phantom measurement and Eclipse predicted near surface (skin) dose, all data normalized at nominal dmax.

| Field Size (cm²) | 3x3 | 5x5 | 10x10 |
|-----------------|------|------|-------|
| Nominal Depth (mm) | EBT2 (%) | AAA (%) | Attix (%) | EBT2 (%) | AAA (%) | Attix (%) | EBT2 (%) | AAA (%) |
| 0               | 17.8 | 28.8 | 10.1 | 20.4 | 31.2 | 16.0 | 39.0 | 40.0 |
| 2               | 56.7 | 47.5 | 55.9 | 60.6 | 49.1 | 59.9 | 60.3 | 55.1 |
| 4               | 76.6 | 68.5 | 77.9 | 82.0 | 69.4 | 80.6 | 80.7 | 72.9 |
| 6               | 86.2 | 83.2 | 87.9 | 85.6 | 83.6 | 89.8 | 90.4 | 85.7 |

Table 2. Phantom measurements for gantry angle 30°. Attix chamber and EBT2 phantom measurement and Eclipse predicted near surface (skin) dose, all data normalized at nominal dmax.

| Field Size (cm²) | 3x3 | 5x5 | 10x10 |
|-----------------|------|------|-------|
| Nominal Depth (mm) | EBT2 (%) | AAA (%) | Attix (%) | EBT2 (%) | AAA (%) | Attix (%) | EBT2 (%) | AAA (%) |
| 0               | 20.6 | 22.7 | 12.4 | 20.9 | 25.6 | 18.3 | 35.0 |
| 2               | 62.5 | 43.6 | 61.2 | 60.5 | 45.9 | 64.3 | 51.8 |
| 4               | 82.0 | 68.1 | 82.7 | 85.6 | 68.6 | 84.0 | 71.8 |
| 6               | 88.2 | 84.8 | 91.9 | 84.6 | 84.6 | 92.3 | 86.5 |

Table 3 shows the reference depths of the Attix chamber and EBT2 film in water equivalent depths at nominal 0 mm depth. Table 4 shows the MC calculated doses. The MC calculated dose values were higher than the Attix data by up to 3.5%.

Table 3. Reference depths of Attix chamber and EBT2 film in water equivalent depths. The reference depth of EBT2 film is at the centre of the active layer and the material density for each layer is taken from Sutherland et al. [14].

| Detector | Water Eq. Depths (mm) |
|----------|-----------------------|
| Attix    | 0.0480                |
| EBT2     | 95 µm side 0.122      |
|          | 190 µm side 0.254     |

Table 4. Monte Carlo calculated build-up region dose for gantry angle 0°. (* Interpolated)

| Field Size (cm²) | 3x3 | 5x5 | 10x10 |
|-----------------|-----|-----|-------|
| Depth in water (mm) | *0.048 | 10.7 | 13.2 | 18.7 |
|                 | 0.070 | 12.3 | 14.6 | 20.2 |
|                 | *0.122 | 14.9 | 17.2 | 22.5 |
|                 | *0.254 | 19.6 | 21.8 | 26.8 |
|                 | 1.000 | 42.0 | 43.4 | 47.3 |
|                 | 2.000 | 58.3 | 59.4 | 62.6 |

3.2. Comparison between in vivo dose measurement and Eclipse AAA predicted near surface dose

Table 5 shows the comparison between EBT2 film measurements and Eclipse AAA predicted near surface doses. The maximum patient skin dose estimated from EBT2 film was between 7.5-19.5 Gy per course, which differed by -23.1% to +69.3% from the Eclipse prediction. Underestimation of the surface dose by Eclipse (for patient 8 and 9) occurred for posterior-oblique beams passing through the immobilization device.

Not all the in vivo measurements were carried out with the thinner polyester layer (75 µm) facing the beam. The dose difference due to asymmetric EBT2 film construction can be estimated from the MC calculation data, where up to +4.8% is found for two measurement depths representing different film orientations for the entrance beam (Table 4). The effect could be more significant for oblique
beam entry. For the in vivo films placed between the skin and the immobilization vacuum bag, the dosimetric effect of film orientation would be insignificant.

The near surface dose estimated from Eclipse plan is subject to inherent uncertainty associated with the definition of mean electron density at the calculation voxel at the skin/air interface and spatial resolution and position of the dose matrix from which dose is interpolated at a particular point. The dosimetric resolution of AAA calculation (~2.5 mm) needs to be considered when comparing with the near surface dose values reported from the Attix, EBT2 and MC measurements/calculation (48 µm – 1 mm). For build-up region dosimetry, the estimated uncertainties of 2% and 2.7% have been reported for the Attix chamber and EBT2 film, respectively [8,12].

Table 5. Comparison of Eclipse AAA algorithm predicted near surface dose and in vivo skin dose estimated from the EBT2 film measurement for nine lung SBRT treatments (2011 – 2012)

| Patient | Eclipse AAA (Gy) | In vivo EBT2 film | Difference (%) |
|---------|-----------------|------------------|---------------|
| 1       | 15.0            | 10.4             | +44.2         |
| 2       | 15.0            | 13.6             | +10.3         |
| 3       | 17.0            | 17.0             | 0.0           |
| 4       | 15.7            | 15.0             | +4.7          |
| 5       | 12.7            | 7.5              | +69.3         |
| 6       | 10.0            | 9.4              | +6.4          |
| 7       | 18.3            | 16.8             | +8.9          |
| 8       | 15.0            | 19.5             | -23.1         |
| 9       | 18.0            | 19.4             | -7.2          |

4. Conclusion
Discrepancies have been noted between the measurements (Attix, EBT2 film) and the Eclipse AAA predicted doses. Further study is required for film dosimetry to be fully applicable for in vivo skin dose measurement for SBRT treatment, which will include EBT3. To better model the electron contamination, further investigation is necessary to evaluate the effect of more accurate build-up region depth dose data, together with optimization of electron contamination source models within AAA. The Eclipse dose prediction in the presence of immobilization devices and the modeling accuracy of build up and build-down effects needs further investigation and future work will also include the Acuros XB algorithm.

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