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Accuracy of In-Field and Out-Field Doses Calculated by Analytical Anisotropic and Pencil Beam Convolution Algorithms: A Dosimetric Study

Osman Vefa GÜL[1*]

[1]Selçuk Üniversitesi Tıp Fakültesi Radyasyon Onkolojisi A.D. Selçuklu/Konya Türkiye

Keywords

In-Field Dose

Out-of-Field Dose

TLD

Abstract

Out-of-field doses may affect the formation of secondary cancers, especially in radiosensitive organs, in patients treated with radiotherapy. The aim of this study is to investigate the in-field dose and out-of-field dose accuracy of Eclipse's analytic anisotropic algorithm (AAA) and pencil beam convolution (PBC) algorithms using TLDs. A tissue equivalent phantom containing a total of 21 measurement points at a depth of 5 cm from the anterior and posterior was created. Using Eclipse AAA and PBC algorithms in TPS, 100 MU for AP/PA fields and 95 cm source-skin distance (SSD) were planned. In-field measurement points including isocenter were 3, 5, 7 and 11 points for 3x3, 5x5, 7x7 and 10x10 cm2, respectively. Measuring points outside the field edge were 38, 36, 34 and 30 points for 3x3, 5x5, 7x7 and 10x10 cm2, respectively. In-field point dose values calculated by TPS for different fields were compared with TLD doses measured at the same location. The difference between in-field dose estimation and TLD measurements of both algorithms was generally below 1%. The difference between TPS and TLD was found to be 4.41% for the 10x10 cm2 irradiation field, due to the field edge at a distance of 5 cm from the isocenter. As the field size decreased, the out-of-field dose calculation performance of the AAA and PBC algorithms was adversely affected. For the 10x10 cm2 irradiation field, the TLD measurements and the out-of-field point dose difference of the PBC algorithm were found to be 39.40%. This difference was at most 12.06% for the AAA algorithm. The Eclipse TPS is good at calculating the in-field dose but underestimates the off-field dose. In out-of-field dose calculation, the AAA algorithm gives more accurate results than the PBC algorithm. Additionally, the smaller the field size, the worse the outfield dose accuracy. The use of in vivo dosimeters is recommended in order to estimate the out-of-field dose with great accuracy in radiotherapy.

Cite

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Author ID (ORCID Number)

O. V. Gül, 0000-0002-6773-3132

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1. INTRODUCTION

Cancer is one of the most serious health problems today. Many patients with cancer receive radiotherapy alone or simultaneously. The most important rule in radiotherapy is to ensure that the surrounding healthy tissue and risky organs receive the minimum dose while the tumor receives the maximum dose. In radiotherapy, patient treatment doses are calculated with treatment planning systems (TPS) that have the dosimetric information of the treatment devices loaded. As treatment techniques improve, the importance of computational algorithms increases. Treatment Planning Systems make dose calculations using different algorithms. These Algorithms are measurement-based, model-based or Monte Carlo based (Bosse et al., 2020). In measurement-based algorithms, using water phantom in treatment fields determined for reference conditions; percent deep dose, dose profile, and dose efficiency measurements are used (Abazarfard et al., 2021). In order to calculate the dose of TPS in radiotherapy, some measurements must be taken in the water phantom first. Percent deep dose and dose profile measurements need to be made for different fields and depths. Thanks to these measured data, TPS tries to accurately estimate the dose distribution in different depths and heterogeneous fields (DePew et al., 2018). Pencil Beam Convolution (PBC) creates the dose matrix by convolving the dose kernel with the

*Corresponding Author, e-mail: vefagul@selcuk.edu.tr

functions of the irregular areas. In the PBC algorithm, the pen beam kernel defines the dose distribution of the very fine beam entering the water equivalent medium. Pencil beam kernels are obtained by measuring central axis deep dose and beam off-axis ratio data. Anisotropic Analytical Algorithm (AAA) algorithm, a new photon dose calculation in Eclipse TPS started to be used. The AAA model provides fast and accurate dose calculation for photon beams, even in regions with complex tissue heterogeneities. Dose calculation algorithms include separate convolution patterns for primary photons, out-of-focus photons, contaminated electrons, and photons scattered from beam-limiting devices. Primary photons are photons emitted from a primary source, expressed as a point source located on the target surface. Out-of-focus photons are the photons scattered from the flattening filter and primary collimators. AAA also takes into account tissue heterogeneities and anisotropic 3D neighborhood of a radiation-matter interaction. Accurate modeling of out-of-field doses in radiotherapy is of great importance for clinical evaluation (Wang & Ding, 2014). During radiotherapy, areas outside the target volume are exposed to radiation due to scattered photons. Out-of-field doses may affect the formation of secondary cancers, especially in radiosensitive organs, in patients treated with radiotherapy (Bahreyni Toossi et al., 2018). Thyroid, breast, ovaries and lenses are among these radiosensitive organs. Although the level of radiation these organs are exposed to is low, it increases the risk of secondary cancer. It is important to determine the accuracy of the doses calculated by TPS algorithms in order to minimize the risk of secondary cancer. Doses taken out of the field by patients who are pregnant or with pacemakers are very important in clinical decisions. In-field dose success of radiotherapy TPS is high, but it cannot show this success in out-field dose calculation. Among the factors that negatively affect the failure of TPS in calculating the out-field dose are the sharp dose drop at the edge of the field and the formation of secondary radiation. Radiation therapy requires quality control at every stage. Some measurements need to be taken for the quality control of the plans prepared for the patients, the treatment planning system, and the treatment device. For this purpose, dosimetric equipment such as ion chambers of various volumes, thermoluminescent dosimeters (TLD), and film dosimeters are used. TLDs are used in clinics for purposes such as determining critical organ doses, investigating dose distribution in complex geometries, validating treatment planning, and controlling new treatment techniques in radiation therapy applications. Although the failure of TPS to calculate out-of-field dose is known, there are not enough studies in the literature (Shine et al., 2019). Howell et al. (2010) evaluated the out-of-field dose performance of the AAA algorithm with TLD in Eclipse TPS and found that the AAA algorithm underestimated over 40% of the out-of-field dose depending on the distance (Howell et al., 2010). Alghamdi and Tajaldeen (2019) evaluated the in-field and out-field dose calculation accuracy of five different algorithms for media with different densities. As a result of the measurements, they found that the AAA and PBC algorithms underestimated the out-of-field dose by 40% (Alghamdi & Tajaldeen, 2019).

This dosimetric study, it is aimed to compare the in-field and out-field dose calculation accuracy of AAA and PBC algorithms used by Eclipse TPS with TLD measurements.

2. MATERIAL AND METHOD

Phantom Irradiation

For the irradiated phantom setup, 9 pieces of 1cm thick and 1 piece 0.5cm thick RW3 (PTW, Freiburg, Germany) phantom of 40cm x 40cm dimensions were used. In addition, a 0.5 cm thick tissue equivalent bolus with adhesive properties was used. In our study, TLD-100 chips were used, and the effective atomic number is 8.14. TLD-100 chips do not produce artifacts as they are close to the human tissue effective atomic number of 7.42. TLD-100 chips were placed at the measurement points determined before Computed tomography (CT). Because TLDs are tissue equivalent, they became the reference for measurement points in the phantom. TLDs were placed 1 cm apart in the bolus to determine measurement points. The preliminary steps for preparing the measurement phantom are shown in Figure 1. The anterior and posterior depth of TLDs was 5 cm. Computed tomography (CT) images of the created phantom were obtained on the Toshiba Aquilion CT device with a slice thickness of 1 mm, and then TPS was transferred. Necessary dosimetric measurements were made before the treatment. The difference between the measurements obtained and the acceptance tests of the linear accelerator was found to be within 1%.

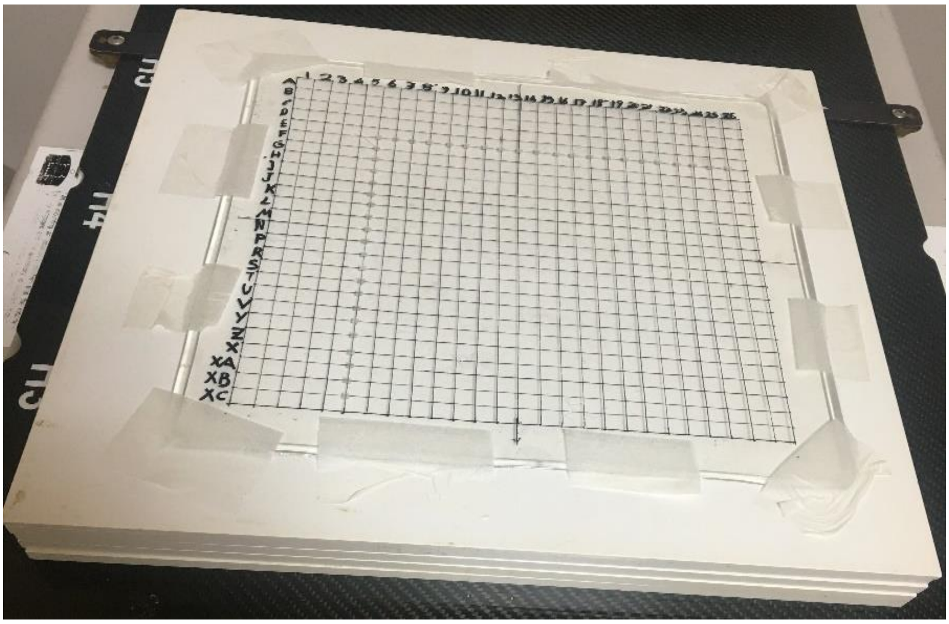

Figure 1. *Preliminary steps to prepare the measurement phantom*

Treatment Planning

For all irradiation fields, the isocenter point was set to 5 cm for anterior and posterior depths and the source-skin distance (SSD) was set to 95 cm. The irradiation setup is shown in Figure 2. The irradiation was carried out in the Varian DHX linear accelerator device with 80 multileaf collimators (MLC) at 6 MV photon energy. X-ray was applied at 300 MU/min. In the AAA and PBC algorithms, dose calculations were made with a 2 mm grid size. In TPS, plans were made to irradiate 100 MU from AP and PA to different open fields using Eclipse AAA and PBC algorithms. These open fields were 3x3, 5x5, 7x7 and 10x10 cm^2. In-field measurement points including isocenter were 3, 5, 7 and 11 points for 3x3, 5x5, 7x7 and 10x10 cm^2, respectively. Measuring points outside the field edge were 38, 36, 34 and 30 points for 3x3, 5x5, 7x7 and 10x10 cm^2, respectively. In-field and out-of-field doses calculated in both algorithms were measured on the x and y axes, then averaged for each axis.

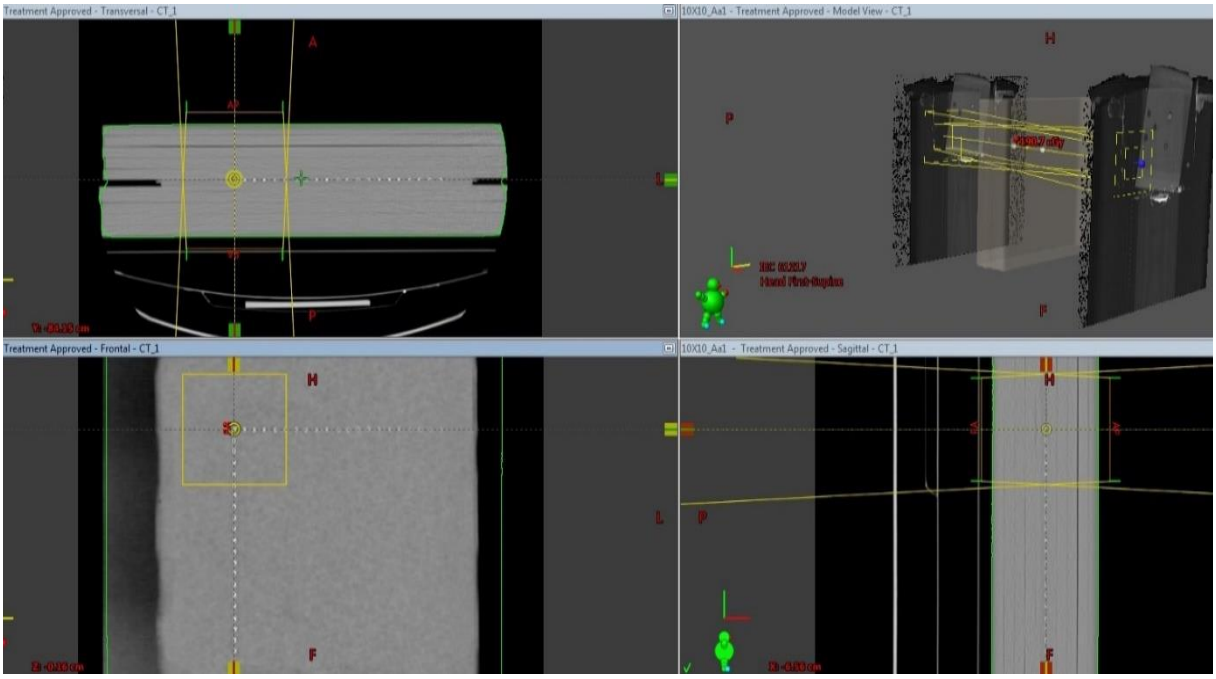

Figure 2. *Measuring points and irradiation set-up in the phantom*

Calibration of TLDs

TLD, which can measure independently of many factors, is accepted as the most suitable in-vivo dosimetry system. In this study, 3.2 mm x 3.2 mm x 0.9 mm chip-shaped TLD-100 dosimeters obtained by doping natural lithium fluoride (LiF) with Mg and Ti were used. 150 TLD-100 chips were used for TLD calibration. TLD-100 chips were baked in TLD oven for 1 hour at 400°C and 2 hours at 100°C. All TLDs were exposed to a dose of 1 Gy in a Varian DHX linear accelerator device at a depth of 1.5 cm with 6 MV photon energy in a 10x10 cm^2 field. 96 TLDs with irradiation reproducibility within 1% were selected for the study. The reader calibration factor (RCF), which is the conversion coefficient to be used to convert the phototube current in microcoulomb (µC) taken from the reader to the absorbed radiation dose, was determined. In order to ensure that the reading values of the selected TLD chips have similar sensitivity, a weighting factor called the element correction factor (ECC) specific to each chip was determined. Since the determined ECC factors are specific to each chip, the chips are named to avoid confusion.

In-Field Dose Measurement with TLDs

Point doses calculated in TPS and measured by TLDs were compared for each field. After each TLD was individually packaged, it was placed at the measuring points. Measurements were repeated 3 times for each point determined before CT. 2 TLDs were placed at each measurement point to minimize the error. In-field dose measurement was performed at 3, 5, 7 and 11 measurement points for 3x3, 5x5, 7x7 and 10x10 cm2, respectively. A preliminary read annealing for irradiated TLD chips was performed at 100ºC for 10 minutes. Doses were measured with TLDs for each area and point. The mean and standard deviation of the measured doses were calculated.

Out-of-Field Dose Measurement with TLDs

Dose measurement points were determined starting at a distance of 1 cm from the field edge. The number of these measurement points was 38, 36, 34 and 30 for 3x3, 5x5, 7x7 and 10x10 cm^2 irradiation fields, respectively. Dose measurement with TLDs was repeated 3 times for each field. Pre-reading annealing process was applied to read TLDs exposed to radiation. The point doses measured by TLDs and calculated by TPS were compared for different irradiation fields.

Statistical Analysis

In the current study, percentage differences between TPS and TLD doses were evaluated. Analysis of AAA, PBC and TLD doses was performed using Paired Sample t-test.

3. RESULTS AND DISCUSSION

The mean dose differences (%) between in-field doses measured by TLD and calculated by AAA and PBC algorithms are shown in Table 1. For the 3x3cm^2 irradiation field, TLD measurements at the isocenter point and the in-field dose difference calculated by TPS were -0.24% and -0.34% for the AAA and PBC algorithms, respectively. For the 3x3cm^2 irradiation field, no significant difference was found between AAA and PBC algorithms for isocenter point doses (p=0.072). For the 5x5 cm^2 irradiation field, point dose measurements on the x and y axes at 1 and 2 cm distance from the isocenter were taken separately and then the average was calculated. Accordingly, the difference between in-field point doses calculated by the AAA and PBC algorithms and measured by TLD was less than 0.75%. For the 7x7cm^2 irradiation field, the difference between TLD measurement and point doses calculated by AAA and PBC algorithms was less than 0.7%. For a 10x10 cm^2 irradiation field, the point dose difference between TLD and TPS up to 4 cm distance is approximately 1%. However, due to the edge of the field at a distance of 5 cm, in-field dose measurement by TLD and calculated by TPS increased to 4.41%. For the 10x10 cm^2 irradiation field, a significant difference was found between the point doses calculated by the AAA and PBC algorithms at a distance of 5 cm (p=0.00). The in-field dose distribution measured by TLD and calculated by TPSs is shown in Figure 3. The mean dose differences (%) between out-field doses measured by TLD and calculated by AAA and PBC algorithms are given in Table 2. For the 3x3cm^2 irradiation field, TLDs could measure the dose up to 19 cm outside the field, while the TPS was able to calculate up to 8 cm. As the field size decreased, the out-of-field dose calculation performance of the AAA and PBC algorithms was adversely affected. For the 10x10 cm2 irradiation field, the

TLD measurements and the out-of-field point dose difference of the PBC algorithm were found to be 39.40%. This difference was at most 12.06% for the AAA algorithm. For all irradiation fields, the AAA algorithm was able to measure the dose at a distance of 12 cm from the edge of the field. The farthest distance that the PBC algorithm could measure was 15 cm. The out-of-field dose distribution measured by TLD and calculated by TPSs is shown in Figure 4. Although radiation was measured with TLD at different distances from the edge of the field, it was observed that the out-of-field dose calculation capability of both algorithms was limited.

Table 1. *Mean dose differences (%) between in-field doses measured by TLD and calculated by AAA and PBC algorithms*

	Field Size (cm^2)											
	3 X 3			5 X 5			7 X 7			10 X 10		
Meas. points	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)
Iso.	-0.25	-0.34	168.92±0.26	-0.28	-0.56	178.25±0.39	-0.09	-0.29	181.82±0.10	-0.54	-0.38	189.88±0.57
1	-0.17	-0.06	162.22±0.24	-0.23	-0.27	177.80±0.55	-0.05	-0.18	181.90±0.48	-0.26	-0.32	189.74±0.60
2	-	-	-	-0.73	-0.67	171.18±0.41	+0.03	-0.06	181.41±0.65	-0.19	-0.24	189.73±0.52
3	-	-	-	-	-	-	-0.68	-0.65	173.98±2.33	-0.44	-0.59	189.33±0.93
4	-	-	-	-	-	-	-	-	-	-0.72	-1.02	185.66±1.99
5	-	-	-	-	-	-	-	-	-	-1.90	-4.41	91.76±5.37

Table 2. *Mean dose differences (%) between out-field doses measured by TLD and calculated by AAA and PBC algorithms*

	Field Size (cm^2)											
	3 X 3			5 X 5			7 X 7			10 X 10		
Meas. points	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)	AAA (%)	PBC (%)	TLD Mean ± SD (cGy)
1	-4.12	-3.49	5.53±0.85	-7.37	-6.18	7.63±0.41	-11.67	-15.19	10.78±0.56	-4.51	-8.76	11.75±0.86
2	-35.09	-34.57	4.02±0.07	-14.81	-13.85	5.18±0.20	+2.13	-5.79	6.47±0.43	-2.15	-31.68	7.89±0.19
3	-63.47	-62.62	3.31±0.08	-25.72	-25.13	3.58±0.15	-4.62	-5.04	4.76±0.16	+6.07	-34.90	5.10±0.70
4	-67.00	-67.29	2.46±0.04	-39.08	-38.56	3.06±0.10	-11.07	-14.50	3.44±0.30	-4.98	-39.40	4.01±0.46
5	-57.09	-58.29	1.41±0.07	-39.43	-41.13	2.12±0.14	-1.34	-6.63	2.23±0.17	+1.10	-30.99	2.71±0.56
6	-62.64	-62.60	1.08±0.07	-40.26	-45.14	1.50±0.18	-9.13	-10.68	1.74±0.17	-1.93	-23.86	2.02±0.33
7	-61.92	-62.48	0.67±0.13	-21.11	-30.83	0.90±0.05	-17.47	-28.88	1.34±0.41	-1.32	-30.56	1.59±0.16
8	-82.12	-81.76	0.56±0.02	-34.23	-42.20	0.78±0.02	-10.02	-14.04	0.89±0.02	+9.36	-17.38	1.11±0.24
9	-	-	0.49±0.01	-31.06	-32.06	0.59±0.01	-10.19	-4.32	0.67±0.04	+8.09	-2.38	0.84±0.05
10	-	-	0.37±0.03	-33.68	-35.87	0.47±0.01	-13.65	-13.27	0.58±0.03	-3.92	-16.45	0.79±0.03
11	-	-	0.30±0.01	-49.25	-48.88	0.40±0.01	-9.09	-7.49	0.44±0.02	-4.03	-3.22	0.62±0.02
12	-	-	0.26±0.02	-49.05	-48.87	0.39±0.01	-28.48	-3.78	0.42±0.02	-12.06	-12.24	0.58±0.02
13	-	-	0.24±0.01	-	-	0.31±0.01	-	-38.05	0.34±0.03	-	-11.59	0.44±0.03
14	-	-	0.21±0.01	-	-	0.26±0.02	-	-38.81	0.32±0.03	-	-6.90	0.42±0.02
15	-	-	0.18±0.01	-	-	0.21±0.01	-	-32.48	0.29±0.02	-	-4.87	0.41±0.02
16	-	-	0.16±0.01	-	-	0.20±0.01	-	-	0.22±0.02	-	-	-
17	-	-	0.14±0.01	-	-	0.18±0.01	-	-	0.19±0.01	-	-	-
18	-	-	0.12±0.01	-	-	0.16±0.01	-	-	-	-	-	-
19	-	-	0.12±0.02	-	-		-	-	-	-	-	-

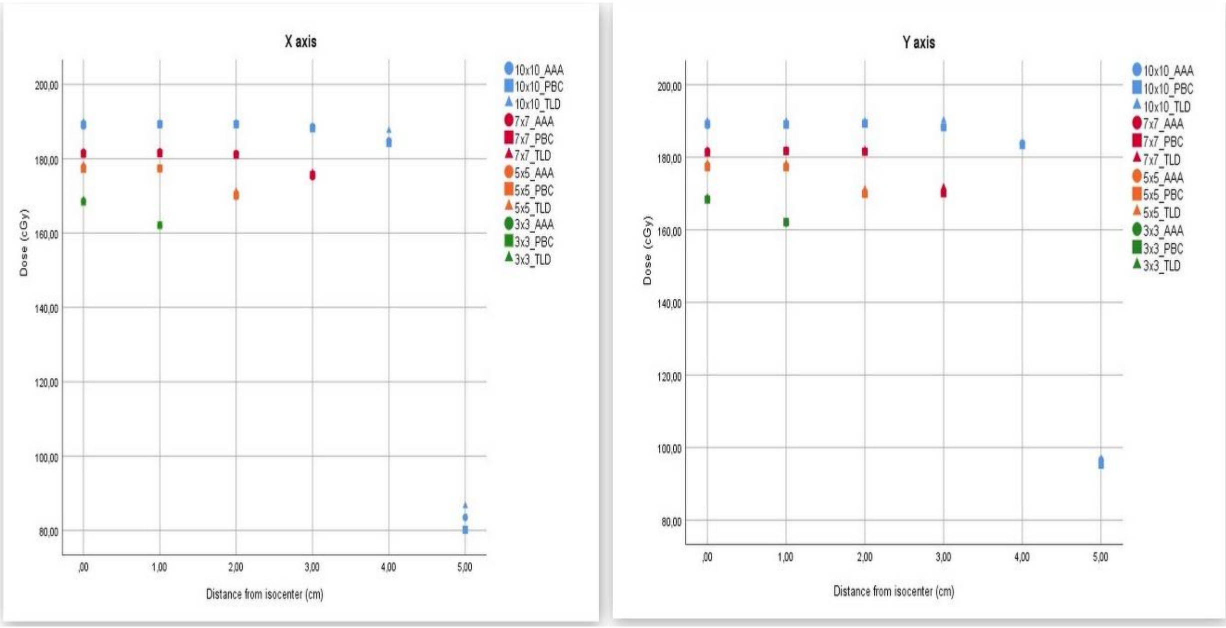

Figure 3. *In-field point dose distribution measured by TLD and calculated by AAA and PBC algorithms*

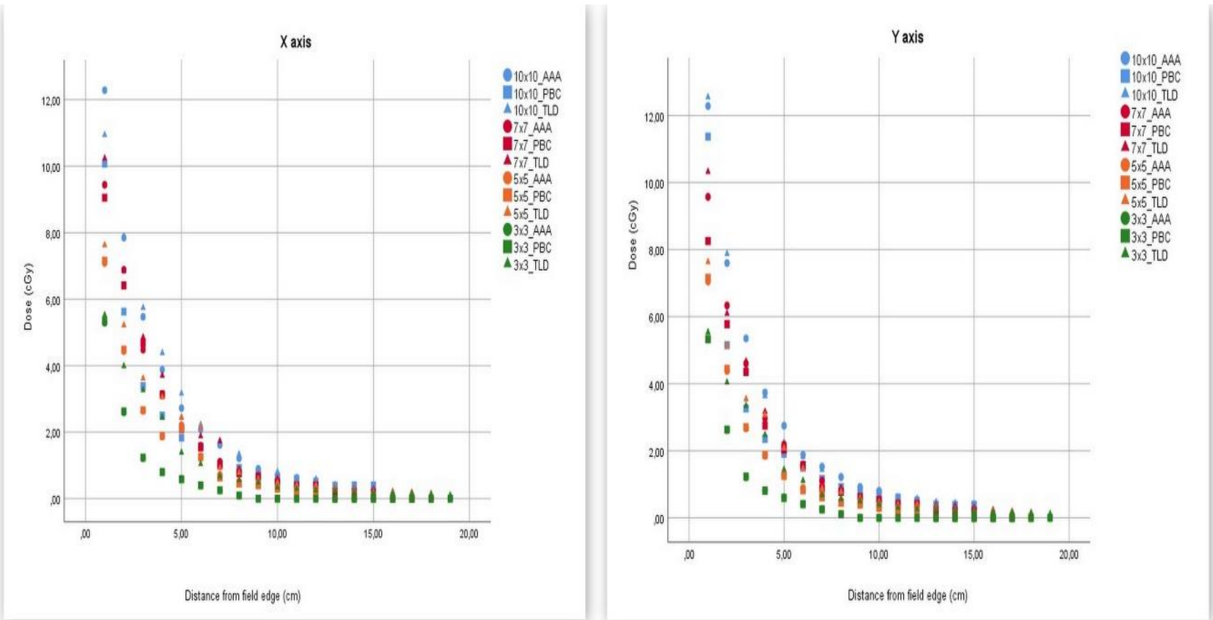

Figure 4. *Out-of-field point dose distribution measured by TLD and calculated with AAA and PBC algorithms*

In this dosimetric study, we examined the accuracy of in-field and out-field doses calculated by Eclipse AAA and PBC algorithms for different fields. Two different algorithms gave similar results with TLD measurements for in-field dose calculation. Out-of-field doses may affect the formation of secondary cancers, especially in radiosensitive organs, in patients treated with radiotherapy. Accurate estimation of out-of-field doses in radiotherapy is important to minimize the risk of secondary cancer. The results show that the AAA and PBC algorithms underestimate out-of-field doses when compared with TLD measurements. The AAA algorithm calculates the out-of-field dose calculation with less error than the PBC algorithm, but it is not sufficient. For the 10x10cm^2 irradiation area, the PBC algorithm and the AAA algorithm underestimate 40% and 12.06%, respectively. These underestimation rates increase as the irradiation field size decreases.

Howell et al. (2010) aimed to measure the accuracy of the out-field dose estimated by the AAA algorithm for a given clinical treatment in the Varian Clinac 2100. They compared doses calculated in TPS and measured by TLD for 238 points. They emphasized that the AAA algorithm could underestimate out-of-field doses by 40% (Howell et al., 2010). In our current study, we found that the AAA algorithm erroneously predicted the dose for 10x10, 7x7, 5x5 and 3x3 cm^2, approximately 12%, 28%, 48%, and 82%, respectively.

Huang et al. (2013) evaluated the accuracy of Pinnacle3 TPS out-field dose calculations for IMRT treatment plans with Anthropomorphic phantom and TLDs. They stated that accurate dose estimation of TPS is inversely proportional to distance. They emphasized that for the three IMRT treatment plans studied, TPS underestimated the dose by an average of 50% (Huang et al., 2013). In the IMRT treatment technique, each field is divided into small sub-fields. The out-of-field dose estimation results of TPS in our study were similar to those of Huang et al. (2013). In our study, it was found that for the $5x5cm^2$ irradiation field, TPS underestimated approximately 49% at a distance of 12 cm from the edge of the field. For the 3x3 irradiation field, the TPS at 8 cm distance underestimates approximately 80%.

Bahreyni Toossi et al. (2018) examined the extra-field dose at different distances in breast irradiation. They found that TPS underestimated the dose by 39%, especially at the edge of the field and at long distances (Bahreyni Toossi et al., 2018). Our research was conducted by Bahreyni Toossi et al. (2018), gave parallel results. It has been observed that TPS underestimates dose for different fields. For the 10x10 irradiation field, the dose underestimated by TPS was approximately 12% and 39% for the AAA and PBC algorithms, respectively.

Sánchez-Nieto et al. (2020) investigated the accuracy of doses estimated by TPS for 10x10 cm^2 field with 6 MV photon energy in Elekta Axesse linear accelerator using dosimetric methods. They stated that TPS was successful in the field, but underestimated by about 13% outside the field edge (Sánchez-Nieto et al., 2020). In our study, both algorithms were found to be successful in calculating in-field dose, but it was seen that they greatly underestimated the out-of-field dose depending on the field size.

Acun-Bucht et al. (2018) aimed to examine the validation of doses calculated by TPS using ion chambers and TLDs. They measured doses of off-axis points 2 cm and 4 cm from the isocenter with TLDs. Acun-Bucht et al. (2018) found the difference between TPS and TLD doses at 2cm and 4cm distance from the isocenter of approximately 3% and 4%, respectively (Acun-Bucht et al., 2018). In our current study, the difference between TLD and TPS doses for 2 cm and 4 cm distances from the isocenter is less than 1%.

Alghamdi and Tajaldeen (2019) evaluated the in-field and out-field dose calculation accuracy of five different algorithms for media with different densities. According to the results of measurements made in water density, the in-field dose difference was 0.39% and 0.43% for the AAA and PBC algorithms, respectively. In addition, as a result of the measurements, they found that the AAA and PBC algorithms underestimated the out-of-field dose by 40% (Alghamdi & Tajaldeen, 2019). In our study, the intra-field dose difference calculated by TLD measurements and TPS was less than 1%. For 10x10 cm2, it was seen that the PBC algorithm underestimated the out-of-field dose by approximately 39%. This rate was approximately 12% for the AAA algorithm.

Gul et al. (2021) investigated the out-of-field fetal dose of a patient who received breast radiotherapy in the first 3 months of pregnancy using a human equivalent phantom. The fetal dose at a distance of 25.84 cm from the lower limit of the target volume was calculated as 0 cGy in the AAA algorithm. TLD measurements ranged between 3-16 cGy. In our current study, in parallel with Gul et al. (2021), AAA and PBC algorithms were found to be insufficient in calculating out-of-field dose at a distance of 19 cm from the edge of the field.

4. CONCLUSION

In this study, we investigated the in-field dose and out-of-field dose accuracy of Eclipse TPS using TLDs. The Eclipse TPS is good at calculating the in-field dose, but underestimates the off-field dose. In out-of-field dose calculation, the AAA algorithm gives more accurate results than the PBC algorithm. Additionally, the smaller the field size, the worse the outfield dose accuracy. Out-of-field doses may affect the occurrence of secondary cancer, especially in radiosensitive organs, in patients receiving radiotherapy. In order to minimize the risk of secondary cancer, it is important to determine the accuracy of the in-field and out-field doses calculated with

TPS algorithms. Out-field doses taken by pregnant patients or patients with pacemakers are crucial in clinical decisions. The use of in vivo dosimetry is recommended for accurate determination of out-of-field dose in radiotherapy of patients who are pregnant or have pacemakers.

CONFLICT OF INTEREST

There is no conflict of interest.

REFERENCES

Abazarfard, M., Azadeh, P., & Mostaar, A. (2021). Dose calculation accuracy for photon small fields in treatment planning systems with comparison by Monte Carlo simulations. *Polish Journal of Medical Physics and Engineering*, *27*(3), 181-190. doi:10.2478/pjmpe-2021-0022

Acun-Bucht, H., Tuncay, E., Darendeliler, E., & Kemikler, G. (2018) Absolute dose verification of static intensity modulated radiation therapy (IMRT) with ion chambers of various volumes and TLD detectors. *Reports of Practical Oncology & Radiotherapy*, *23*(4), 242-250. doi:10.1016/j.rpor.2018.04.001

Alghamdi, S., & Tajaldeen, A. (2019). Evaluation of dose calculation algorithms using different density materials for in-field and out-of-field conditions. *Experimental Oncology*, *41*(1), 46-52. doi:10.32471/exp-oncology.2312-8852.vol-41-no-1.12529

Bahreyni Toossi, M. T., Soleymanifard, S., Farhood, B., Mohebbi, S., & Davenport, D. (2018). Assessment of accuracy of out-of-field dose calculations by TiGRT treatment planning system in radiotherapy. *Journal of Cancer Research and Therapeutics*, *14*(3), 634-639. doi:10.4103/0973-1482.176423

Bosse, C., Narayanasamy, G., Saenz, D., Myers, P., Kirby, N., Rasmussen, K., Mavroidis, P., Papanikolaou, N., & Stathakis, S. (2020). Dose Calculation Comparisons between Three Modern Treatment Planning Systems. *Journal of Medical Physics*, *45*(3), 143-147. doi:10.4103/jmp.jmp_111_19

DePew, K. D., Ahmad, S., & Jin, H. (2018). Experimental Assessment of Proton Dose Calculation Accuracy in Small-Field Delivery Using a Mevion S250 Proton Therapy System. *Journal of Medical Physics*, *43*(4), 221-229. doi:10.4103/jmp.jmp_33_18

Gul, O. V., Inan, G., & Basaran, H. (2021). Dosimetric comparison of different radiotherapy techniques to determine the absorbed fetal dose in pregnant patients with left-sided breast cancer. *Arab Journal of Nuclear Sciences and Applications*, *54*(4), 94-101. doi:10.21608/ajnsa.2021.69536.1456

Howell, R. M., Scarboro, S. B., Kry, S. F., & Yaldo, D. Z. (2010). Accuracy of out-of-field dose calculations by a commercial treatment planning system. *Physics in Medicine & Biology*, *55*(23), 6999-7008. doi:10.1088/0031-9155/55/23/S03

Huang, J. Y., Followill, D. S., Wang, X. A., & Kry, S. F. (2013). Accuracy and sources of error of out-of field dose calculations by a commercial treatment planning system for intensity-modulated radiation therapy treatments. *Journal of Applied Clinical Medical Physics*, *14*(2), 186-197. doi:10.1120/jacmp.v14i2.4139

Sánchez-Nieto, B., Medina-Ascanio, K. N., Rodríguez-Mongua, J. L., Doerner, E., & Espinoza, I. (2020). Study of out-of-field dose in photon radiotherapy: A commercial treatment planning system versus measurements and Monte Carlo simulations. *Medical Physics*, *47*(9), 4616-4625. doi:10.1002/mp.14356

Shine, N. S., Paramu, R., Gopinath, M., Jaon Bos, R. C., & Jayadevan, P. M. (2019). Out-of-Field Dose Calculation by a Commercial Treatment Planning System and Comparison by Monte Carlo Simulation for Varian TrueBeam®. *Journal of Medical Physics*, *44*(3),156-175. doi:10.4103/jmp.jmp_82_18

Wang, L., & Ding G. X. (2014). The accuracy of the out-of-field dose calculations using a model-based algorithm in a commercial treatment planning system. *Physics in Medicine & Biology*, *59*(13), N113-28. doi:10.1088/0031-9155/59/13/n113