Original

Assessment of Dose Calculation Accuracy of Monaco Treatment Planning System for Effective Wedge Angle in Internal Wedged Fields using Two Different Analytical Methods

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ABSTRACT

Background: In radiotherapy, the accuracy of dose calculation systems plays a key role in the treatment of cancer patients.

Objective: The current research aimed to evaluate the dose calculation accuracy of Monaco Treatment Planning System (TPS) in estimating the Effective Wedge Angle (EWA) using two different mathematical methods: Elekta formula and ICRU-24 formula.

Material and Methods: In this experimental study, EWAs for different field sizes (5×5, 10×10, 15×15, 20×20, 25×25, and 30×30 cm^2) at standard angles (15°, 30°, 45°, and 60°) were computed by the Monaco TPS using two different analytical methods. The practical EWAs were measured according to the conditions outlined in the Elekta formula and the ICRU-24 formula, and these measurements were compared with the results derived from the TPS.

Results: The planned and measured EWAs are consistent with the Elekta formula, and the error value was less than ±0.5 in all radiation fields and EWAs. In the ICRU-24 formula, the maximum deviation was ±2.6° between the computational and practical EWAs.

Conclusion: The Elekta-based analytical method demonstrates a good agreement between planned and measured EWAs, while the ICRU-24 formula exhibited the greatest discrepancies.

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Keywords

Radiometry; Radiotherapy; X-Rays; Internal Wedge; Effective Wedge Angle; Elekta Formula; ICRU-24 Formula

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Introduction

Radiotherapy is one of the three primary approaches for treating various cancer types globally. Successful cancer treatment relies on delivering sufficient dose coverage to the target while minimizing exposure to normal and vital tissues. Wedge filters are employed in radiotherapy to improve dose uniformity within the target volume [1]. Various auxiliary devices are utilized in radiotherapy, including physical, motorized, and dynamic wedges, which can tilt the isodose curve relative to the beam Center Axis (CAX). By combining these devices with other radiation fields, it is possible to achieve the desired dose distribution within the tumor volume. Currently, computer-controlled wedge systems, including internal, dynamic, and virtual aspects, play a crucial role in radiation therapy, enhancing dose uniformity within the target volume [1]. Automated wedge filters offer several advantages, such as eliminating the risk of physical injury to both operator and patients, reducing the need to handle physical wedges, shortening treatment times, accommodating more patients, decreasing operator fatigue, and allowing for customizable Wedge Angles (WAs) instead of standard ones. In 3D Conformal Radiation Therapy (3DCRT), wedge filters are commonly employed to treat tumors in various anatomical regions, including the brain, breast, and pelvis. However, the steep dose gradients associated with these treatments can create hot spots that pose significant risks to critical organs, such as the optic nerves, heart, esophagus, and rectum [2-5]. Precise Treatment Planning System (TPSs) are essential for accurate dose calculations and effective dose delivery systems via linear accelerators (Linacs) equipped with specialized tools, including wedge filters, Multi-Leaf Collimators (MLC), and Electronic Portal Imaging Devices (EPID).

According to the International Commission on Radiation Units and Measurements (ICRU-83), the delivered radiation dose should remain within -5% to +7% of the prescribed dose [6]. This standard necessitates rigorous Quality Assurance (QA) protocols for these systems [7]. Several QA protocols related to the dose calculation and delivery systems provide valuable insights into the agreement levels (or acceptable error margins) between measured and calculated doses [8-12]. Consequently, the accuracy of dose calculations must be assessed using different computational algorithms in wedged fields [13].

The dosimetric characteristics of motorized wedges, including Effective Wedge Angle (EWA), wedge factor, and beam hardening, were analyzed for their dependence on WA, field size, and energy. Ilyas et al. [14] found that the EWA was minimally affected by field size, staying within the recommended range (±3%) [8]. Changes in isodose curves have been analyzed in standard wedge fields at different depths [1, 15-20]. Gamit et al. f reported a difference of 9° and 5° between the effective and nominal WAs at photon beam energies of 6 Million Volts (MV) and 15 MV, respectively [1]. Ramya et al. [21] noted that motorized wedges are influenced by both energy and field size, with the largest discrepancies observed at 6 MV energy and the smallest field size (5×5 cm^2), while the lowest mismatches occurred at 15 MV energy with the largest field size (20×20 cm^2). Behjati et al. [17] evaluated the dosimetric characteristics of Elekta's motorized wedge and found a maximum difference of 10° between planned and motorized WAs. Comparative data for assessing and contrasting the motorized EWA using the Elekta and ICRU-24 formulas is currently lacking in the literature.

The presence of a wedge filter in the beam path alters the quality of the radiation beam, reducing its intensity and increasing its average photon energy due to beam hardening effect. Consequently, the slope of the isodose curves varies depending on the degree of beam hardening in different sections of the internal wedge, leading to changes in the EWA. To enhance the accuracy of dose calculations, it is crucial to understand the extent of beam hardening in the wedge filter during treatment planning, a factor that should be integrated into computerized TPSs [16]. The dose calculation accuracy of Monaco TPS in determining the EWA using two different analytical methods has not been previously investigated. This study aimed to compare planned EWAs with measured EWAs using two different methods: the Elekta and ICRU-24 formulas. While prior research [1, 14, 16, 17, 22] has focused on a limited number of radiation fields involving wedges, this study explores WAs across a broader range of radiation fields, from 5×5 to 30×30 cm^2. This study provides a comparative analysis using the Elekta and ICRU-24 formulas to evaluate the accuracy of the Monaco TPS in estimating EWAs across a wide range of radiation fields.

Material and Methods

This experimental study in conducted in two phases as descriptive research in the radiotherapy department at Shahid Madani Hospital in Tabriz, Iran, from September 2023 to March 2024. The study aimed to assess the accuracy of the Monaco TPS in generating wedged isodose curves. EWAs were computed at various angles and radiation fields using the TPS, employing two analytical methods: the Elekta and ICRU-24 formulas. The calculations for EWAs based on these formulas utilized the guidelines provided in the Elekta user manual [22-24] and ICRU-24 protocol [14, 25-27]. Subsequently, EWAs were derived from practical measurement data across different angles and radiation fields using both analytical approaches. The outcomes from the TPS data were compared with practical measurements to evaluate the accuracy of Monaco TPS computations against experimental results. Standard Nominal Wedge Angles (NWAs) of 15°, 30°, 45°, and 60° were selected along wedged fields with square dimensions of 5, 10, 15, 20, 25, and 30 cm^2. The EWA within TPS was established through Forward Planning, whereby the desired NWA was input into the Monaco TPS to obtain the Monitor Unit (MU) values corresponding to both the wedged and open fields. To compute the EWA using the Elekta and ICRU-24 formulas, it is sufficient to gather the requisite point dose data at specified depths (single-point dose data for Elekta formula and four-point dose data for ICRU-24 formula) from the TPS, which were then applied in their respective equations to derive the EWA values. The EWA generated by the internal wedge of the Elekta machine was calculated based on the MU values obtained from the TPS. The MU values for both the wedged and open fields were then irradiated onto a water phantom, with point dose values measured at the specified depths using the Farmer Chamber. These dose values enabled the determination of EWAs using both the Elekta and ICRU-24 formulas.

Elekta Motorized Wedge

Elekta employs a 60-degree remote-controlled motorized physical wedge filter integrated within the accelerator head to produce various WAs. This wedge is composed of lead-antimony alloy (96% lead and 4% antimony, 3.2 kg $PbSb_4$) with a density of 11.1 g/cm^3. This remote-controlled wedge filter can lead to select WAs ranging from 1° to 60°. The motorized technique combines radiation doses from both open field and the physical wedge along the beam path, resulting in wedge-shaped isodose curves [28].

To evaluate the accuracy of TPS calculations in the context of wedged fields, all necessary data for commissioning the Collapsed Cone convolution (CCC) algorithm, including depth dose percentage data and dose profiles, were collected and input into the TPS. Subsequently, audit tests, including the wedged field (Case No. 7 from International Atomic Energy Agency (IAEA) Technical Documents No. 1583 (TECDOC-1583) [29]) were simulated using the Monaco TPS. Radiation was performed on the Computerized Imaging Reference Systems (CIRS) phantom, and dose values at the designated points were obtained using the Farmer Chamber, leading to the assessment of discrepancies between calculated and measured doses in wedged fields. The results indicated a good agreement between the algorithm calculations and empirical measurements.

Elekta Formula

The equations utilized in the Elekta method [22-24] for determining EWAs are as follows:

$$F = \frac{\tan\theta}{\tan\psi} \quad (1)$$

Where F is defined as weight factor, θ is the effective wedge angle, and Ψ is considered the maximum wedge angle for a specified field size and depth.

In a wedged field, the weight factor (F in Equation 1) indicates the dose percentage of the motorized wedged and open field. This weight factor ranges of 0 (fully open field) to 1 (fully wedged field), with intermediate values representing partially wedged field. The Monaco TPS can ascertain the necessary coefficients (dose or MUs) for each field individually. By employing an appropriate combination of calculated weighting factors, isodose distribution corresponding to desired Effective Wedge Angle) EWAs (can be achieved, ranging from 0° to 60°.

$$D_w = D_t \times F \quad (2)$$

Where D_w is the dose that the angular part of the beam receives in the central axis of the beam at depth d and D_t is the total dose reached in the central axis of the beam at depth d.

$$D_o = D_t - D_w = D_w \times \frac{1-F}{F} \quad (3)$$

Where D_o is the dose that the open part of the beam receives in the central axis of the beam at depth d.

All calculations were performed at a depth of 10 cm from the surface of the water phantom, with a Source-to-Surface Distance (SSD) of 100 cm. The gantry and collimator angles were set to 0°.

ICRU-24 Formula

According to the ICRU report 24 [14, 25-27], the following formula was employed to derive EWAs using the ICRU-24 method:

$$Wedge\ Angle = \theta = \tan^{-1}\left[\frac{(D_p - D_q)/\Delta d}{(D_9 - D_{11})/2}\right] = \tan^{-1}\left[\frac{(\Delta dose)/(width)}{(\Delta dose)/(depth)}\right] \quad (4)$$

D_9 represents the dose at a depth of 9 cm, and D_{11} is the dose at 11 cm along the central axis of the beam. D_p and D_q are lateral coordinates at a depth of 10 cm, where for angles of 15° and 30°, they equal ± field width/4, and for angles of 45° and 60°, they equal ± field width/6. Δd denotes the distance between the lateral coordinates Dp and Dq on either side of the central axis. All measurements were conducted 100 cm from the Source-to-Axis Distance (SAD) and 10 cm below the surface of the water phantom, with gantry and collimator angles set to 0°.

Using these two analytical methods, the Elekta and ICRU-24 Formulas, we calculated and measured internal motorized EWAs.

Calculated Effective Wedge Angle

The Monaco TPS (version 5.11.03, Elekta, Crawley, England), utilizing the CCC algorithm, was employed to calculate the EWAs across various square fields and standard WAs. A virtual water phantom, matching the dimensions of a 3D water phantom (50×50×50 cm^3) with a relative electron density of 1, was utilized in the TPS. The central axis of the radiation fields was defined centrally within the phantom, ensuring sufficient thickness from the radiation field edges to account for lateral scattering rays. The configuration for the Monaco plan employed the SSD technique, with an SSD of 100 cm for the Elekta formula. For the ICRU-24 formula, the planned EWA was defined as the slope of the isodose contour (%50) at a standard depth of 10 cm on the CAX at a 100 cm SAD. After defining the virtual water phantom in the TPS and applying specific settings according to the Elekta and ICRU-24 formulas, wedged fields with standard NWAs (15°, 30°, 45°, and 60°) were designed across six different square fields (5×5 to 30×30 cm^2 at 5 cm intervals). An X-ray beam with an energy of 6 MV was utilized in all plans, with both collimator and gantry angles set to zero degrees. Following calculations in the Monaco TPS, all requisite point dose data were obtained for computing EWAs. The calculated EWAs were subsequently extracted using the Elekta and ICRU-24 formulas. Figure 1 illustrates the position of the points necessary for calculating the EWA using the ICRU-24 method for a field size of 10×10 cm^2 with an NWA of 45°.

According to the ICRU-24 formula [14, 25-27], the maximum acceptable deviation of the EWA from the nominal standard value should remain within ±2°. For instance, for an NWA of 15°, the permissible range for the EWA lies between 13° and 17°.

Measured Effective Wedge Angle

To obtain the measured EWAs, it was essential to collect the dose information corresponding to the required points based on the Elekta and ICRU-24 formulas by measuring absolute doses in a water phantom. A Pole To Win (PTW) Motorized 3D water Phantom system (MP3) (PTW-Freiburg, Germany), equipped with an electrometer and a Farmer-type ionization chamber (model 30013 PTW with a sensitive volume of 0.6 cm^3), was utilized to determine the measured EWAs. Figure 2 depicts the setup employed for measuring the EWA with the Elekta linear accelerator and the PTW water phantom. The Technical Reports Series No. 398 (TRS-398) dosimetry protocol [30] was followed to obtain the absolute dose at the target points. After setting up the phantom, the Farmer chamber was positioned at predetermined locations in the wedge/open field as outlined in the TPS with specified MUs. According to the planned WA and the TPS report, the MUs for both the internal wedge field and the open field were exposed using the linear accelerator.

To obtain the absolute dose from dosimeter readings, a series of correction coefficients must be applied to the raw data. These corrections include the $N_{D,w,Q0}$ factor (absorbed dose calibration factor to water), $K_{T,P}$ factor (water temperature and air pressure correction

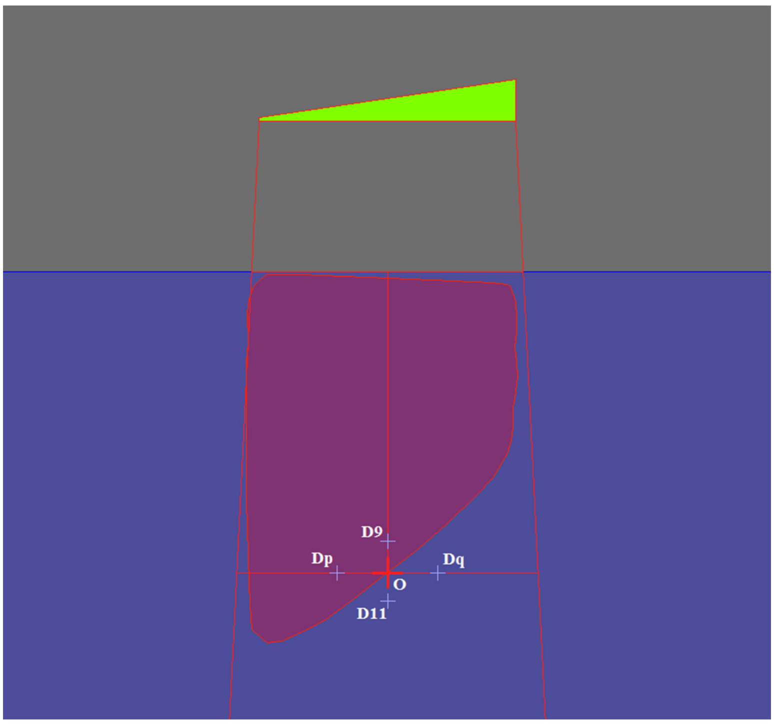

Figure 1: A graphical representation of the Monaco plan was set up to determine the effective wedge angles using International Commission on Radiation Units and Measurements (ICRU-24) formula (field size 10×10 cm^2, wedge angle 45°). Point O is positioned at the isocenter.

Figure 2: Absolute dosimetry was conducted using a linac (Elekta Synergy Platform) in conjunction with a Pole To Win (PTW) Motorized 3D water Phantom system (MP3) to measure the effective wedge angles.

factor), K_{elec} factor (electrometer calibration factor), K_{pol} factor (polarity correction factor), K_s factor (saturation or ion recombination correction factor), and $K_{Q,Q0}$ (radiation quality correction factor). Once these correction coefficients are applied, the absolute dose at the specified depth can be determined. Consequently, practical EWAs can be calculated using the relationships defined for the Elekta and ICRU-24 formulas. The positional accuracy of the PTW MP3 water tank scanner arm was verified using high-precision dial gauges, with mechanical precision estimated at ±0.1 mm across all three coordinate axes.

Results

The values of the measured and planned EWAs for all relevant field sizes and WAs, as determined by the Elekta and ICRU-24 formulas, are detailed in Tables 1 to 4. Also, Tables 1 to 4 present the discrepancies between the planned EWAs and measured EWAs in terms of degrees and percentages.

Data analysis using the Elekta formula indicates that the angle difference between the EWAs is within ±0.5° (ranging from -0.34° to 0.37°). In contrast, the analysis of the ICRU-24 formula revealed a deviation between the calculated and measured EWAs was approximately ±2.6°, ranging from -2.58° to 1.63°.

A maximum deviation of -2.58° with a NWA of 60° using the ICRU-24 formula was observed for a 10×10 cm^2 field size, while the Elekta formula yielded a maximum deviation of 0.37° at a NWA of 45° for the same field size. Table 5 presents the weighting factors necessary for generating isodose curves associated with Elekta's motorized EWAs across four standard angles. These factors were extracted from TPS calculations. According to Elekta's guidelines, by appropriately combining two radiation fields, one with a 60° physical motorized wedge and another without a wedge (open field), it is possible to achieve the desired EWA within the range of 0° to 60°. This method can lead to the adjustment of isoline curves at a depth of 10 cm in a water phantom, aligning the slope to meet the provided WA.

Discussion

The objective of this study was to assess

Table 1: Comparison between the Elekta formula and the International Commission on Radiation Units and Measurements (ICRU-24) formula for obtaining measured and planned effective wedge angles across various field sizes at a nominal wedge angle of 15°.

Field size (cm²)	Elekta Formula				ICRU-24 formula			
	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)
5×5	14.68 (-0.32)	14.79 (-0.21)	0.11	0.73	11.61 (-3.39)	10.60 (-4.40)	-1.01	8.74
10×10	14.87 (-0.13)	14.96 (-0.04)	0.09	0.62	12.32 (-2.68)	11.38 (-3.62)	-0.94	-7.62
15×15	15.08 (+0.08)	15.17 (+0.17)	0.09	0.58	13.72 (-1.28)	12.78 (-2.22)	-0.94	-6.84
20×20	15.29 (+0.29)	15.34 (+0.34)	0.05	0.32	14.07 (-0.93)	13.47 (-1.53)	-0.60	-4.23
25×25	15.43 (+0.43)	15.46 (+0.46)	0.03	0.17	14.96 (-0.04)	14.71 (-0.29)	-0.25	-1.67
30×30	15.50 (+0.50)	15.53 (+0.53)	0.03	0.17	15.08 (+0.08)	15.02 (+0.02)	-0.06	-0.42

The values in parentheses indicate the degree of difference from the nominal wedge angle of 15°.

ICRU: International Commission on Radiation Units and Measurements; TPS: Treatment Planning System; EWA: Effective Wedge Angle

Table 2: Comparison between the Elekta formula and the International Commission on Radiation Units and Measurements (ICRU-24) formula for obtaining measured and planned effective wedge angles across various field sizes at a nominal wedge angle of 30°.

Field size (cm²)	Elekta Formula				ICRU-24 formula			
	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)
5×5	29.87 (-0.13)	29.71 (-0.29)	-0.16	-0.54	22.20 (-7.80)	23.83 (-6.17)	1.63	7.34
10×10	30.18 (+0.18)	29.96 (-0.04)	-0.23	-0.75	23.67 (-6.33)	25.18 (-4.82)	1.51	6.40
15×15	30.51 (+0.51)	30.25 (+0.25)	-0.26	-0.86	26.23 (-3.77)	27.77 (-2.23)	1.54	5.86
20×20	30.78 (+0.78)	30.44 (+0.44)	-0.34	-1.09	27.45 (-2.55)	27.98 (-2.02)	0.53	1.91
25×25	30.88 (+0.88)	30.62 (+0.62)	-0.26	-0.85	29.06 (-0.94)	29.59 (-0.41)	0.53	1.83
30×30	30.97 (+0.97)	30.71 (+0.71)	-0.27	-0.86	30.15 (+0.15)	30.16 (+0.16)	0.01	0.02

The values in parentheses indicate the degree of difference from the nominal wedge angle of 30°.

ICRU: International Commission on Radiation Units and Measurements; TPS: Treatment Planning System; EWA: Effective Wedge Angle

Table 3: Comparison between the Elekta formula and the International Commission on Radiation Units and Measurements (ICRU-24) formula for obtaining measured and planned effective wedge angles across various field sizes at a nominal wedge angle of 45°.

Field size (cm²)	Elekta Formula				ICRU-24 formula			
	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)
5×5	44.45 (-0.55)	44.76 (-0.24)	0.32	0.71	37.03 (-7.97)	35.09 (-9.91)	-1.94	-5.24
10×10	44.60 (-0.40)	44.97 (-0.03)	0.37	0.82	39.51 (-5.49)	37.57 (-7.43)	-1.94	-4.92
15×15	44.87 (-0.13)	45.17 (+0.17)	0.30	0.67	41.28 (-3.72)	40.80 (-4.20)	-0.48	-1.16
20×20	45.07 (+0.07)	45.33 (+0.33)	0.26	0.57	42.81 (-2.19)	42.10 (-2.90)	-0.71	-1.66
25×25	45.19 (+0.19)	45.46 (+0.46)	0.26	0.58	43.97 (-1.03)	43.85 (-1.15)	-0.12	-0.27
30×30	45.22 (+0.22)	45.52 (+0.52)	0.30	0.67	44.81 (-0.19)	44.95 (-0.05)	0.14	0.30

The values in parentheses indicate the degree of difference from the nominal wedge angle of 45°.

ICRU: International Commission on Radiation Units and Measurements; TPS: Treatment Planning System; EWA: Effective Wedge Angle

Table 4: Comparison between the Elekta formula and the International Commission on Radiation Units and Measurements (ICRU-24) formula for obtaining measured and planned effective wedge angles across various field sizes at a nominal wedge angle of 60°.

Field size (cm²)	Elekta Formula				ICRU-24 formula			
	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)	Measured EWA (°)	TPS EWA (°)	Deviation (°)	Deviation (%)
5×5	59.85 (-0.15)	59.89 (-0.11)	0.04	0.07	52.65 (-7.35)	50.19 (-9.81)	-2.46	-4.67
10×10	59.90 (-0.10)	59.93 (-0.07)	0.03	0.05	56.44 (-3.56)	53.86 (-6.14)	-2.58	-4.58
15×15	60.01 (+0.01)	60.05 (+0.05)	0.04	0.07	57.65 (-2.35)	56.80 (-3.20)	-0.85	-1.47
20×20	60.14 (+0.14)	60.16 (+0.16)	0.02	0.03	58.25 (-1.75)	57.72 (-2.28)	-0.53	-0.90
25×25	60.36 (+0.36)	60.37 (+0.37)	0.01	0.02	58.86 (-1.14)	59.35 (-0.65)	0.49	0.83
30×30	60.58 (+0.58)	60.59 (+0.59)	0.01	0.02	59.65 (-0.35)	60.23 (+0.23)	0.58	0.97

The values in parentheses indicate the degree of difference from the nominal wedge angle of 60°.

ICRU: International Commission on Radiation Units and Measurements; TPS: Treatment Planning System; EWA: Effective Wedge Angle

Table 5: Weight factors related to standard wedge angles. The data were calculated using Treatment Planning System (TPS).

Monaco calculated wedge angle (°)	Wedged beam weight factor	Open beam weight factor
15	0.40	0.60
30	0.65	0.35
45	0.83	0.17
60	1	0

the dose calculation accuracy of the Monaco TPS EWA produced by the internal motorized wedge filter, comparing results derived from the Elekta and ICRU-24 formulas. To determine the calculated EWA in Monaco TPS and the measured EWA using the Elekta Synergy machine, we employed two different methods. The first method utilized the relationships outlined in the Elekta user manual [23] (Elekta formula), while the second relied on the formulas from the ICRU-24 protocol (ICRU-24 formula). After calculating the EWAs and measuring them with both Elekta and ICRU-24 formulas across four standard angles and six different radiation fields, we analyzed the discrepancies between these angles using both analytical approaches.

The results presented in Tables 1 to 4 indicate that for all the EWAs obtained through the Elekta formula, variations in the size of the radiation field did not significantly affect deviation values. However, analysis of Elekta formula revealed that for all relevant angles, an increase in radiation field size corresponded with a slight increase in the calculated and measured EWAs. Notably, these values remained very close to their respective NWAs. Furthermore, across all examined fields at an angle of 60°, the difference between the calculated and measured EWAs was nearly negligible.

Data processing using the ICRU-24 formula indicates that as the radiation field size decreases, the discrepancy between planned and measured EWAs increases, with the effect being particularly pronounced at smaller wedge angles. For a field size of 5×5 cm^2 at a nominal angle of 15°, the maximum discrepancy reached -8.74%. Consequently, the ICRU-24 formula exhibited the greatest fluctuations or differences at the smallest field dimensions (5×5 cm^2). It can also be inferred from the ICRU-24 formula that for each standard WAs studied, both measured and planned EWAs increased with larger radiation field sizes; however, the rate of increase in ICRU-24 EWAs was significantly greater than that of the Elekta EWA. Nonetheless, the ICRU-24 EWAs were notably distant from their corresponding standard NWAs, especially as discrepancies widened with decreasing field size and WA. This phenomenon can be interpreted the increasing contribution of the 60° physical motorized wedge as the wedge angle increases, leading to a longer duration of exposure (or MU) in the wedged field. As indicated in Table 5, the weighting factor for the wedged beam rises with an increase in WA, which in turn enhances beam hardening effects from the motorized wedge filter. This increase also leads to a greater number of scattered rays produced. The inadequate modeling of these effects in TPS calculations suggests that Monaco's CCC algorithm may not fully account for the impacts of beam hardening and scattered radiation on dose distribution. The dose is calculated by convolving the Kernel with the Total Energy Released per unit Mass (TERMA). Factors such as the tilt of the kernel, X-ray absorption based on voxel density, and variations in the energy fluence spectrum can affect this calculation. Thus, it is likely that the discrepancy between planned and actual EWA widens as the WA increases. We found that similar to earlier findings [1, 17, 21, 31] as the radiation field and wedge angle decrease, the differences become more noticeable.

Our study results show that the ICRU-24 formula, which depends on the slope of the isoline curve and four specific dose points, adds more uncertainty to dose calculations than the Elekta formula. In contrast, the Elekta formula uses just one measurement point and determines the EWA as a ratio of the dose (or MUs) between a fully wedged beam and an open beam. Further research is warranted to accumulate more data and insights, and the incorporation of advanced dosimetric techniques could be beneficial, such as two-dimensional dosimetry with films.

The findings of this study revealed that, for the ICRU-24 formula and NWAs of 15° and 30°, the percentage error between the calculated and measured EWAs exceeded ±2% in seven radiation fields. However, as the NWA increased to 45° and 60°, the number of fields with significant discrepancies decreased to two radiation fields at each WA. This study highlights that the largest deviations in planned versus actual EWAs were considerably lower than previously reported deviations (maximum –2.58°). Furthermore, the results show that the deviations in practical EWAs from the planned values across various radiation fields remained within the acceptable uncertainty range of ±2° [25, 32]. Our findings align with those of previous studies [21, 25, 31, 32]; although some reports suggest that their deviations exceeded the proposed uncertainty range [1, 17].

Comparative analysis of the Elekta and ICRU-24 formulas showed consistent agreement with the Elekta formula, while the ICRU-24 was consistent only in radiation fields of 20×20 cm^2 or larger. Similar deviations have been reported in other studies [1, 17].

Nurjannah et al. [33] found that increasing wedge angles reduce doses to the Planning Target Volume (PTV) and Organs-at-Risk (OAR). Our results confirm that higher wedge angles enhance beam hardening, reducing patient radiation exposure. Future studies should aim to analyze larger datasets and foster multi-institutional collaborations, and encompass a broader array of treatment scenarios to validate our findings. Additionally, the development of novel computational methods and more advanced dosimetric techniques would provide significant values.

In summary, this study offers valuable insightful into the performance of various EWA computation methods. While TPSs like Monaco are essential in radiotherapy, it is crucial to recognize their limitations and validate their outputs through comparative analysis.

Conclusion

This study primarily compares two computational methods (Elekta and ICRU-24 formulas) for estimating EWAs and assesses the accuracy of the Monaco TPS CCC algorithm. Results indicate that the Elekta formula shows minimal discrepancy between planned and measured EWAs, with errors about ±1% across all radiation fields and standard wedge angles, while the ICRU-24 formula has a deviation of ±9%. The Elekta formula's reliance on dosimetric data from a single point at CAX results in lower discrepancies, whereas the ICRU-24's use of four points outside CAX increases dose uncertainty and errors in EWA determination.

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Authors' Contribution

The idea for the study was conceived by A. Bahari, H. Rezaeejam, and M. Molazadeh. A. Bahari, SS. Zakariaee, and A. Tarighatnia were involved in material preparation, data collection, and data curation. H. Rezaeejam and M. Molazadeh guided and consulted on the statistical analysis. A. Bahari, SS. Zakariaee, and A. Tarighatnia writing the first draft of the manuscript. Introduction of the paper

was written by A. Bahari. A. Bahari and SS. Zakariaee gather the images and the related literature. A. Bahari, A. Tarighatnia, and SH. Rezaeejam implemented the method. The results section was carried out by A. Bahari and M. Molazadeh. M. Molazadeh proofread and supervised the research work. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The Ethics Committee of Tabriz University of Medical Sciences approved the study protocol (Ethic code: IR.TBZMED.REC.1403.013).

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Conflict of Interest

None

Data Availability Statement

The data that support the findings of this study are available on request.

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