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Assessing Tomotherapy Performance Post-Linac Replacement: A Dosimetric Comparison with Manufacturer's Gold Data

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Abstract

This study aimed to experimentally compare dosimetric measurement data obtained after linac replacement in a Tomotherapy HiArt system with the "gold data" provided by the manufacturer, according to the acceptance criteria recommended by AAPM TG-148. Energy quality ($TPR_{1.5/10}$), percentage depth dose (PDD), transverse and longitudinal beam profiles, and patient treatment plan quality assurance (QA) measurements were performed and compared with gold data. The difference between the gold and measured data in the energy quality measurement was 0.5%. In the PDD measurements, the difference in dmax values remained at a maximum of 0.9 mm, and the $PDD_{20/10}$ ratio remained below 1%. Agreement within the 1% tolerance limits was also observed in the transverse and longitudinal profiles. Furthermore, the patient QA measurements were in agreement with the results obtained using the previous linac. The findings demonstrated that all measurements remained within the TG-148 criteria, indicating that linac replacement did not significantly affect system performance. These results confirmed that the TomoTherapy HiArt system provides reliable and accurate dosimetric measurements following linac replacement, ensuring consistent and high-quality patient treatment delivery.

Keywords: Tomotherapy, AAPM TG-148, Dosimetric measurement, Gold standart data, Linac replace

1. Introduction

The Helical Tomotherapy system enables intensity-modulated radiotherapy (IMRT) using a 6 MV linear accelerator mounted on a ring gantry. It is designed to deliver highly modulated IMRT and achieve a significant dose reduction in regions containing critical structures [1, 2]. The TomoTherapy system, which utilizes a mounted 6 MV linear accelerator, differs in design from conventional linacs. Key design distinctions include the absence of a flattening filter, enhanced collimator shielding, distinct treatment and imaging operating modes, and narrow fan beam transmission [2]. It features a table structure suitable for simultaneous gantry movements and provides image guidance using megavoltage computed tomography (MVCT).

In the Tomo system, the patient table moves synchronously towards the 85 cm diameter gantry aperture while the gantry rotates continuously, enabling sectional irradiation. Unlike conventional linacs, the Tomo collimation system generates a 40 cm flattening filter-free (FFF) fan beam with user-selectable longitudinal field lengths (slice widths) of 5, 2.5, and 1 cm [2]. Because of the significant differences between the Tomo system and conventional linacs, a unique quality assurance program is essential. Given that Tomo is a relatively recent modality with helical irradiation integrated treatment planning, the American Association of Physicists in Medicine (AAPM) Task Group 148 (TG 148) was established to review and provide recommendations for routine quality assurance of helical tomotherapy units [3]. This report summarizes the Task Group's findings and aims to equip clinical medical physicists with the necessary understanding of the technology to establish an independent and comprehensive quality assurance program for helical tomotherapy units [3]. This serves as a guide for evaluating the frequency of dosimetric and mechanical tests for the Tomo system and the acceptance criteria for the test results. In addition to differences in treatment application, beam modeling for the Tomo treatment planning system (TPS) also differs from that for conventional linacs. While a conventional linac TPS constructs a machine model based on user-measured

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data, the Tomo TPS is preloaded with a machine model based on a standard "gold data" beam dataset [4]. Although gold data are not user-adjustable, their verification is the user's responsibility. "Standard" or "gold" data accurately represents the specific machine [5]. The AAPM TG-148 recommends measuring a static treatment beam to verify satisfactory agreement with gold data [3]. TG-148 further recommends monthly evaluation of the energy quality tissue phantom ratio ($TPR_{10/1,5}$) and profile agreement between the TPS beam and gold data. Furthermore, following major machine component replacements (e.g., linac, magnetron) or machine upgrades (i.e., version changes) requiring recalibration, a comprehensive quality assurance procedure, including water phantom or solid phantom tests performed by physicists, is necessary to reflect the condition of the machine and verify the agreement of these changes with gold data [3].
This study aimed to conduct an experimental comparison between dosimetric measurement data and gold data in the TomoTherapy Hi-Art system after linac replacement. The data agreement of the system after major component replacement was examined by considering the acceptance criteria recommended by AAPM TG-148.

2. Materials and Methods

The recommended dosimetric measurements including energy quality measurement, percentage depth dose (PDD) and beam profile measurements after linear accelerator change in the Accuray brand Tomotherapy Hi-Art system located in the Radiation Oncology Clinic of Turgut Ozal Medical Center were compared with the gold data of the device. Finally, a patient treatment plan quality assurance (QA) program was used to evaluate the QA results of the previous linac.

2.1. Tomotherapy Hi-Art Device

In this study, Hi Art model Tomotherapy device, which produces 6 MV FFF photon beams, has a source-skin distance (SSD) of 85 cm and a field width of Jaw_1, $Jaw_{2.5}$ and Jaw_5 cm, was used [6].

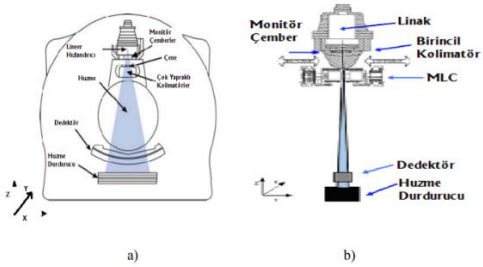

Figure 1. a) Tomotherapy gantry design, b) radiation source, MVCT X-ray source, detector system, and collimator structure. [7].

2.2. Energy Quality Measurements

In the Tomotherapy system, $TPR_{10/1.5}$ measurements using water-equivalent solid phantoms were performed to determine the energy quality. For $TPR_{10/1.5}$, dose measurements were performed by placing an ionization chamber at depths of 1.5 and 10 cm in a solid water phantom with an SSD of 85 cm. The ratio of the ionization chamber reading at a depth of 10 cm to the reading at 1.5 cm ($D_{10}/D_{1.5}$) was compared with the gold data. A 2% agreement between the gold data result and the measured data result was considered acceptable.

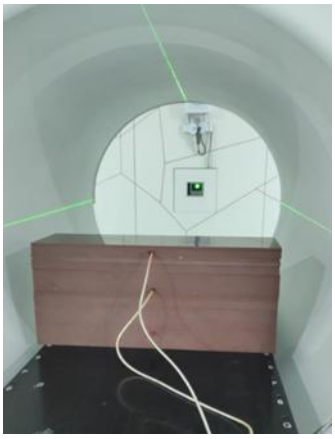

Image 1. Energy quality set up measurement

2.3. Water Phantom Measurements

A PTW MP3-T water designed to fit the gantry structure, with external dimensions of approximately 32 cm (height) × 42 cm (width) × 69 cm (length) and a scanning capability of 28 cm (H) × 60 cm (L), capable of scanning a 40 cm cross-plane field at a depth of 20 cm, was used for PDD and beam profile measurements in the tomotherapy system.

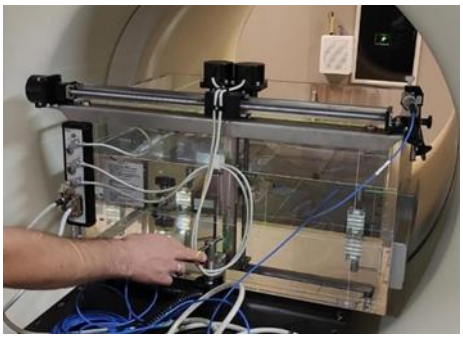

Image 2. PTW Water phantom measurement setup.

For data acquisition using the water phantom in the tomotherapy device, isocenter alignment was performed on the water phantom placed on the treatment table. The position of the ionization chamber relative to the isocenter was determined using image-guided radiotherapy (IGRT). After completing the setup, PDD measurements and transverse and longitudinal beam profiles were measured for each of the Jaw_1, $Jaw_{2.5}$, and

Jaw_5 field sizes and compared with previously modeled gold data.

2.3.1. Percentage depth-dose measurements

In this study, PDD measurements were acquired in the water phantom at measurement depths between 0 and 20 cm for each of the three jaw widths: Jaw_1, $Jaw_{2.5}$, and Jaw_5. In this measurement, which determined the energy consistency of the device, the PDD curves were normalized to 100% for all three field sizes and the maximum dose depth was examined. The agreement between the modeled (gold standard) and measured PDD was evaluated within the acceptance criteria of 2%/1 mm.

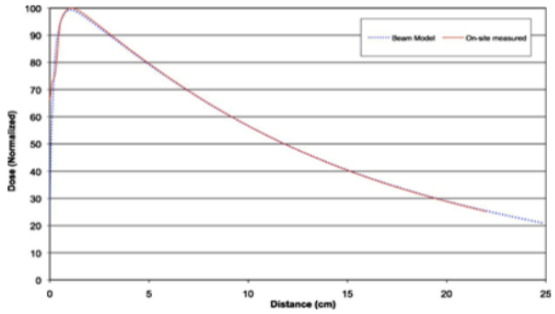

Figure 2. Example of a PDD curve measured in a water phantom at an SSD of 85 cm (for a 2.5x40cm^2 [3].

2.3.1.2. Profile Measurements

Transverse (cone) and longitudinal profiles were measured at a depth of 1.5 cm for Jaw_1, $Jaw_{2.5,}$ and Jaw_5 field sizes in the water phantom.

2.3.1.2.1. Transverse Profile

As the Tomotherapy units did not use a flattening filter, the transverse beam profiles were cone-shaped, as shown in Figure 3. When evaluating the transverse profiles, the data acquired along the central axis of the beam were compared with the modeled data. The agreement between the modeled and measured cone profiles was evaluated within the acceptance limit of 2%/1 mm.

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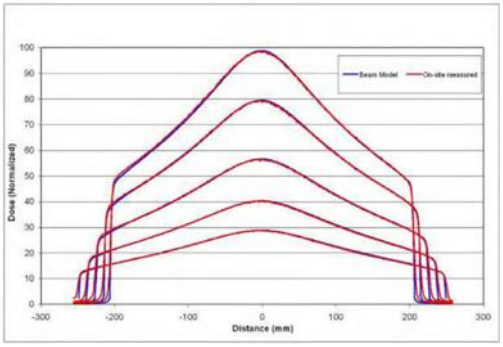


Figure 3. Example of a transverse beam profile measured in a water phantom (2.5x40cm^2). Data were acquired at an SSD of 85 cm and at depths of 15 mm, 50 mm, 100 mm, 150 mm, and 200 mm [3].

2.3.1.2.2. Longitudinal Profile:

The longitudinal beam profile stability test is essentially a slice width test. Longitudinal profiles were acquired in the water phantom for Jaw_1, $Jaw_{2.5}$, and Jaw_5 field sizes, and the full width at half maximum (FWHM) was examined. The agreement between the modeled gold data and measured longitudinal beam data was evaluated within 1% acceptance limits.

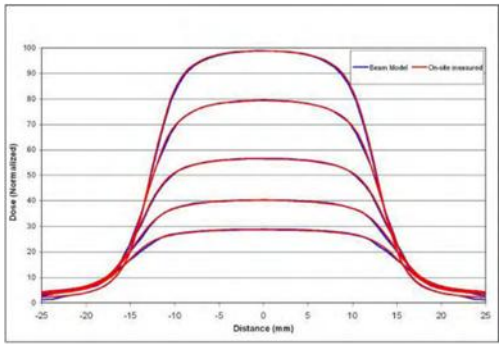
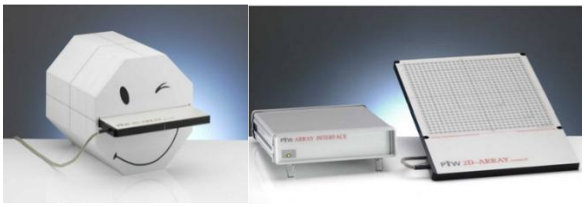


Figure 4. Example of a beam profile measured in a water phantom and the corresponding modeled beam profiles. Data were acquired at an SSD of 85 cm and at depths of 15 mm, 50 mm, 100 mm, 150 mm, and 200 mm [3].

2.4. Patient Treatment Plan Quality Assurance Program (QA)

To evaluate the quality control recommended by Task Group 148 after linac replacement, DQA results of a previously planned cervical treatment plan, which passed the DQA evaluation with 95% agreement before linac replacement, were used as a reference plan. Without any changes to the treatment plan, Repeated QA measurements were performed using a 2D array in a PTW Octavius phantom, and gamma analysis was conducted. A gamma analysis result within 3%/3 mm for the measured QA data was considered an acceptance criterion.



(a) **(b)**

Image 3. (a) PTW Octavius QA phantom, (b) PTW Seven 29 2D array and interface [7].

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3. Results and Discussion

The results of dosimetric measurements performed after linac replacement in the tomotherapy device, guided by TRS 148, including energy quality values, PDD, and transverse and longitudinal profile measurement data, are presented in Tables 1, 2, 3, and 4, respectively. The results of the patient treatment plan quality assurance (QA) program are shown in Figure 7.

3.1.1. Energy Quality Measurements

The ionization chamber readings at D_{10} and $D_{1.5}$ and the $TPR_{10/1.5}$ energy quality value for a 5 × 40 cm^2 field width in a solid phantom for energy quality measurement with the 6 MV photon beam's gold data value are given in Table 1.

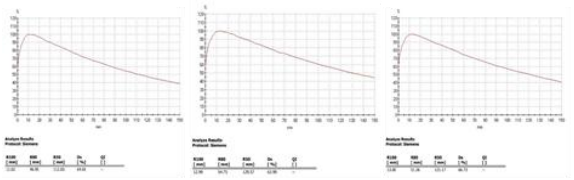
Table 1. Energy Quality $TPR_{1,5/10}$

Parameters	Electrometer Reading Values (nC)		$TPR_{1,5/10}$ (Gold Data) ($D_{10}/D_{1.5}$)	$TPR_{1,5/10}$ (Measured Value) ($D_{10}/D_{1.5}$)	Difference (%)
	Gold Data	Ölçülen Değer			
$D_{1,5}$	12,34	17,13	0,606	0,609	0,5
D_{10}	7,52	10,39			

Looking at the values given in Table 1, while the D_{10} and $D_{1.5}$ ionization chamber reading values are close to each other, the difference between the gold data and the measured data of the $TPR_{1.5/10}$ ratio, which provides the energy quality value, was found to be 0.5%, which is considerably lower than the 2% acceptance criterion limits.

3.2. Percentage Depth Dose Measurement

The dmax, 5, 10, and 20 cm depth profiles of the PDDs measured in the water phantom at three different field



(a) (b) (c)

Figure 5. PDD graphs for Jaw_1, $Jaw_{2.5}$, and Jaw_5 (a,b, and c, respectively)..

The PDD curves show that the beam decreased, indicating the expected dose change depending on the depth.
A comparison of the PDD values measured in the water phantom with the gold data values is given in Table 2 as dmax, PDD_5cm(%), PDD_{10}cm(%), and PDD_{20}cm(%).

The measured and gold data results for the PDD parameters (Table 2) were within the tolerance limits (1%); however, the measured data had slightly higher dmax values and increasing PDD values with depth compared to the gold data. The difference between the data in dmax was found to be 0.9, 0.3, and 0.9 mm for Jaw_1, $Jaw_{2.5}$, and Jaw_5, respectively. For the PDD20/10 values, the difference between the data for the Jaw_1 and Jaw_5 field sizes was less than 1%. No difference was observed between the data for the $Jaw_{2.5}$ PDD20/10 ratio.

Table 2. PDD gold data and measured data values for Jaw_1, $Jaw_{2.5}$, and Jaw_5

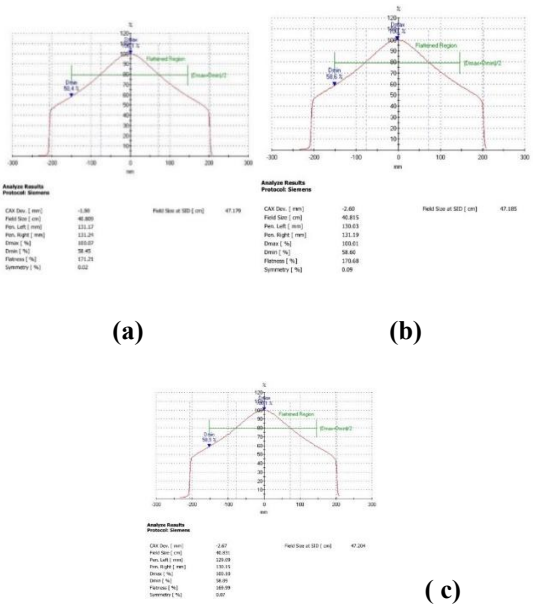
Beam Parameters	Field Size	Gold Data (mm)	Measured data (mm)	Difference (mm)
dmax	Jaw_1	12.0	11.1	0.9
	$Jaw_{2.5}$	12.7	13.0	0.3
	Jaw_5	12.0	12.9	0.9
PDD	**Field size**	**Gold Data (%)**	**Measured data (%)**	**Difference (%)**
PDD_5cm(%)	Jaw_1	77.28	78.40	1.1

	$Jaw_{2.5}$	79.80	80.80	1.0
	Jaw_5	81.90	82.80	0.9
PDD_{10}cm(%)	Jaw_1	53.90	54.30	0.4
	$Jaw_{2.5}$	56.75	57.20	0.5
	Jaw_5	59.90	60.40	0.5
PDD_{20}cm(%)	Jaw_1	37.98	38.40	0.42
	$Jaw_{2.5}$	40.50	40.50	0
	Jaw_5	43.40	44.30	0.9
PDD ($_{20/10}$)(%)	Jaw_1	0.70	0.71	0.01
	$Jaw_{2.5}$	0.71	0.71	0
	Jaw_5	0.72	0.73	0.01

3.3. Profile Measurements

3.3.1. Transverse Profile

The transverse profiles acquired at dmax depth for all field sizes (Jaw_1, $Jaw_{2.5}$, and Jaw_5 cm, and the transverse field width (40 cm) was examined for all field sizes (Jaw_1, $Jaw_{2.5}$, and Jaw_5). When calculating the field width, the distance at which the intensity at the beam edge decreased to 50% of the central axis value in the cone-shaped transverse profile was used as a reference. Figure 6 shows the transverse profiles for the 1 × 40, 2.5x40, and 5 × 40 cm^2 fields, respectively. The gold data and measured data values for the field width calculated in the transverse plane for all the three field sizes are listed in Table 3.



(a) **(b)**

(c)

Figure 6. Transverse profiles of 1x40, 2.5x40, and 5x40 cm^2 fields, respectively a,b,c.

Tablo 3. Comparison of transverse field widths of Jaw_1, $Jaw_{2.5}$, and Jaw_5 with gold standard data.

Field Width (cm^2)	Gold Data (cm)	Measured Data (cm)	% Difference
1x40 cm^2	41.04	40.89	0.24
2.5x40 cm^2	41.06	40.82	0.73
5x40 cm^2	41.07	40.83	0.50

Table 3 shows a comparison of the transverse field width (40 cm) for all three jaw sizes with gold standards. This is within the 1% change acceptance limit according to Task Group 148. According to Table 3, the maximum difference between the reference gold data of the device and the transverse profile data acquired with the water

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phantom after linac replacement was observed in the $Jaw_{2.5}$ field width (0.73%).

3.3.2. Longitudinal Profile

When evaluating the longitudinal profiles acquired at dmax depth in the water phantom at Jaw_1, $Jaw_{2.5}$, and Jaw_5 cm field sizes, the measurement of the slice width was evaluated based on the beam profile stability test for all field sizes (Jaw_1, $Jaw_{2.5}$, and Jaw_5). The longitudinal profiles acquired in the water phantom for all fields are shown in Figure 7. The full width at half maximum (FWHM) was used as a reference for the slice width. The gold data and measured longitudinal beam profile data are listed in Table 4**.**

The consistency of the longitudinal beam profiles acquired at the dmax depth in the water phantom was measured for all used slice widths (Jaw_1, $Jaw_{2.5}$, and Jaw_5). The difference between the measured data and the gold data for all three field sizes was within 1% when considering the full width at half maximum value (Figure 7).

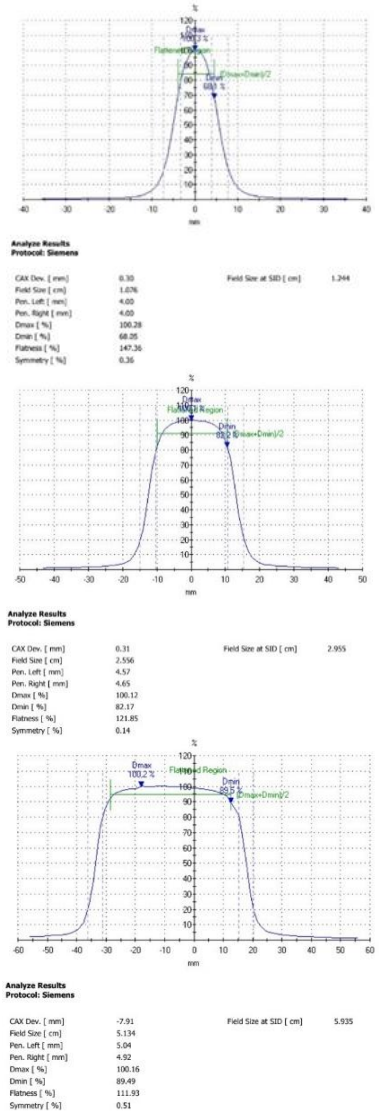


Figure 7. Longitudinal beam profiles of Jaw_1, $Jaw_{2.5}$, and Jaw_5 cm^2 fields, respectively, from left to right.

Table 4. Comparison of longitudinal field widths of Jaw_1, $Jaw_{2.5}$, and Jaw_5 with gold data**.**

Field Width (cm^2)	Gold Data (mm)	Measured Data (mm)	% Difference
1x40 cm^2	10.90	10.96	0.55
2.5x40 cm^2	25.68	25.68	0
5x40 cm^2	51.54	51.54	0

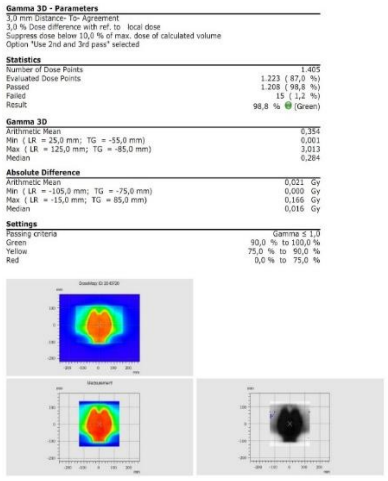
When the slice width differences between the measured and gold data in the longitudinal profiles were evaluated for Jaw_1, $Jaw_{2.5}$, and Jaw_5, it was observed that the difference between the modeled data and the measured data remained below 1% for all three field sizes, whereas the $Jaw_{2.5}$ and Jaw_5 slice widths had the best data agreement (Table 4).

3.4. QA Plan Evaluation

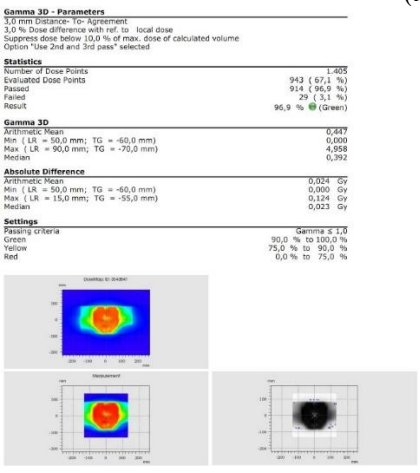
The QA results of the endometrium treatment plan, which had a QA plan made before linac replacement and whose results measured with the 2D array remained within the 3%/3 mm gamma acceptance criteria, are shown in image 4 (a). The QA measurement results of the

treatment plan of the new linac, which had an acceptance criterion of > 95%, are shown in image (b).

Gamma analysis of the dosimetric verification test performed on the phantom-based treatment plan of the QA treatment plan made with the new linac showed that it passed at a rate of 96,9% (İmage 4).From this test, it was concluded that the dosimetric values (such as energy quality and beam profiles), which were within the gold standards in the previous linac system, were compatible with those in the new linac system.



(a)



(b)

Image 4. (a) Old linac QA plan result; (b) new linac QA plan result.

4. Conclusion

In this study, the measurement data obtained after the linac system replacement of the Tomotherapy Hi-ART radiotherapy device were compared with the modeled reference data called "golden data" provided by the manufacturer during installation. Dosimetric measurements (energy quality, beam profiles, and QA/phantom) recommended by Task Group 148 for major component replacement were used to evaluate whether the data were within the acceptance criteria.

According to the AAPM Task Group 148, the $TPR_{10/1,5}$ value should be examined in a solid water phantom for energy quality measurement, and a 2%/1 mm acceptance criterion has been established [3]. Existing dosimetry protocols followed for the output measurement of photon beams from the accelerator require a beam quality correction factor; this beam quality correction factor is related to the quality index of the photon beam [$\%DD(_{1.5/10})$ or $TPR_{20/10}$] [8]. Two methods are used for energy accuracy in tomotherapy systems. The first method involved taking dose measurements at depths of 1.5, 10, and 20 cm with solid water phantoms at an SSD of 85 cm and comparing the results of these measurement ratios with the beam data (gold data) reference value. For energy quality, the $D_{10}/D_{1.5}$ or $D_{20}/D_{1.5}$ values were compared with reference values to check whether they were within 2% agreement. Another method is to use Stepwedge in the Tomotherapy quality control software, TQA [9]. According to the $TPR_{10/1,5}$ measurement results examined using solid water phantoms, the measured value after linac replacement remained within the acceptance criteria of the gold data value. At the same time, the percentage difference between the two values was small (0.5%). This indicates that the stability of the new linac system integrated into the device in terms of energy quality is quite good.

In this study, measurements were taken at depths of 5, 10, and 20 cm for the Jaw_1, $Jaw_{2.5}$, and Jaw_5 cm^2 field sizes in a water phantom for the Dmax and PDD dose measurements, and the results are shown in Table 2. When considering the change in the measured Dmax values in Table 2 for all field sizes, it was observed that the difference between the gold data and measured data showed a maximum change of 0.9 mm. When the PDD change depending on depth in Table 2 was examined, it was observed that the measured data showed a maximum change of 1.1 mm compared to the gold data, and the agreement between the two data was quite good. In the study by Peng et al., which compared the measured data with the reference data using water phantom measurements in a tomotherapy device, they found that although the PDD parameters showed a very good match between the scanning systems, the measured data showed slightly higher dmax and depth-increasing PDD values compared to the reference data, and this change showed an increase of 1.3, 0.4, and 1.4 mm in Jaw_1, $Jaw_{2.5}$, and Jaw5, respectively [5]. It can be said that this increase in Dmax, which was also observed in $Jaw_{2.5}$ and Jaw_5 ın in this study, is due to mm differences in dosimetric center adjustment in setup conditions. For the PDD_5 cm(%), PDD_{10} cm(%), and PDD_{20} cm(%) values, the difference between the gold data and the reference data was observed most in the Jaw1 field size (1.1 mm). This difference in the Jaw1 field size is related to small-field dosimetry. A possible reason for PDD differences in small fields is the volume effect of the ionization chamber [10, 11].

In this study, the $PDD_{20/10}$ ratio between the gold and reference data was within the 1% tolerance limit for all three field sizes. In a study conducted by Langen et al., a 1% comparison tolerance was made by performing a quantitative analysis with the $PDD_{20/10}$ ratio for all three field sizes between the gold data and the measured data for the $PDD_{20/10}$ ratio [3]. Recent studies, such as Chen et al. have similarly demonstrated the critical role of PDD ratio consistency in evaluating linac performance post-replacement, supporting the findings of this study [12].

In this study, the average field-width difference between the transverse beam profiles remained within the 1% tolerance limit for the jaw size (40 cm) for the measured and gold data. TG-148 recommends evaluating the consistency of the cross-plane profiles by comparing the measured profiles with the gold beam data for transverse beam profiles because the stability of the transverse beam profiles is an indication of beam quality consistency and maintains differences equal to or lower than 1% as tolerance limits [3, 13]. This is consistent with the findings of Martínez-Rovira et al. who emphasized the impact of transverse beam uniformity on treatment accuracy in helical delivery systems [14].

The stability of the longitudinal beam profiles in a tomotherapy system is particularly important for helical tomotherapy. The dose delivered to the patient depends on the integration of the longitudinal beam profile shape with table movement. Therefore, if the beam profile changes, the delivered dose will also change. The longitudinal beam profile stability test is essentially a slice-width test, and the full width at half maximum (FWHM) of the beam is recommended for monitoring. The FWHM of the profile should not change by more than 1% [3]. In this study, although the difference between the gold data and measured data in the Jaw_1 field size was 0.6%, no difference was found in $Jaw_{2.5}$ and Jaw_5 field sizes. Consequently, in this study, the longitudinal beam profile, that is, the slice width test, for all three field sizes was well below the tolerance limit. This profile is an important parameter for tomotherapy because the dose shape is continuously superimposed with slight shifts as the patient enters and exits the treatment beam [13]. This situation requires setup sensitivity, and it should not be forgotten that setup verification is required first when out-of-tolerance values are encountered. If the test results continue to fail, corrective actions (such as jaw calibration) should be performed by service engineers.

A patient-specific treatment quality control procedure (QA) is a quality control procedure performed before treatment for each patient to monitor the characteristics of the machine. With the QA plan, tests in planning, and correct shaping of planning steps, phantoms are treated like patients in terms of being subjected to the same imaging, and play a role in ensuring that all steps of the plans that patients will undergo in treatment are within tolerance limits. The tolerance limits were within 95% of the 3%/3 mm gamma acceptance criteria [15]. In this study, the QA of a cervical treatment plan, which was obtained using the previous linac and was within the acceptance limits, was compared with the QA measured after linac replacement in the system, and no difference was found. It can be said that this agreement in the QA results is related to the agreement of the beam center and consistency in dose outputs.

As a result, in this study, in the comparison of the data measured after linac replacement with the gold data under the guidance of Task Group 148, it was observed that all tests, including energy quality, PDD, beam profiles, and the patient QA program, gave results consistent with the gold data. It can be said that the gold data belonging to the Tomo system are in the nature of reference data, and its agreement with the data measured as a result of routine quality assurance protocols or major part replacements in the system is a guide for system performance.

Author Contributions

The entire study design, data analysis, writing, and revision processes were carried out by a single author.

Ethics approval

Not applicable; this phantom-based dosimetric study involved no human participants or patient data.

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