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Acceptance testing of linear accelerators: A multi-institutional analysis of adjustment limits

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ABSTRACT

Background: Users of linear accelerators (linacs) often encounter challenges in understanding the adjustment limits and machine characteristics of the devices. This study analyzed the acceptance test data from linacs installed at multiple facilities to evaluate the adjustment limits for test criteria. ***Materials and Methods:*** Data were collected from eight TrueBeam, four VitalBeam, and one TrueBeam STx models (Varian Medical Systems, Palo Alto, CA, USA) installed between 2015 and 2024. The average values and standard deviations (SDs) for the radiation isocenter, multileaf collimator (MLC), JAW positional accuracy, beam quality, and beam profile (flatness and symmetry) were examined across facilities. ***Results:*** The SD of the radiation isocenter for the gantry and collimator was 0.01, which was smaller than that for the radiation isocenter, including the couch (0.06). The average MLC positional accuracy was less than half of the required tolerance, even though the SD was larger than that of the isocenter acceptance tests. The maximal JAW offset had an average value and SD exceeding >0.2 mm and 0.4 mm, respectively, with the Y JAW exhibiting greater variation than the X JAW. All photon beam quality measurements were within the tolerance of enhanced beam compatibility (≤±0.5). The SD for the flatness was smaller than that for the symmetry for both the in-line and cross-line measurements. ***Conclusion:*** Adjustments to the isocenter using software demonstrated minimal variations across facilities, whereas manual adjustments, including those for the MLC, JAW, beam quality, and profile, exhibited larger SDs.

INTRODUCTION

Cancer treatment includes various modalities, such as surgery, radiotherapy, chemotherapy, targeted therapy, chemodynamic therapy, and ablation therapy [1-3]. In radiotherapy, stereotactic radiation therapy enables precise tumor irradiation, whereas intensity-modulated radiation therapy achieves steep dose distribution to minimize damage to adjacent organs at risk [4-6]. Achieving steep dose gradients and dose concentrations necessitates high accuracy in radiation therapy devices, particularly in terms of parameters such as the isocenter accuracy, multileaf collimator (MLC) positional accuracy, and beam flatness [7]. Manufacturers continuously develop and improve control systems, while users implement rigorous quality control (QC) and quality assurance (QA) measures for radiation doses, geometric parameters, and safety standards [7, 8] to enhance the performance of these devices. Linear accelerator (linac) systems typically have a projected operational lifespan of 10 years, following which vendor support is discontinued owing to the unavailability of replacement parts. Consequently, system updates or replacements become necessary [9].

Acceptance tests are conducted following linac installation to evaluate the machine accuracy. These tests encompass dosimetry and mechanical safety parameters such as the isocenter rotation accuracy, MLC positioning, and photon and electron beam profiles [8, 10, 11]. The methods employed for acceptance testing vary, with the tolerance levels of the manufacturer regularly adjusted based on different measurement tools and vendor policies. High adjustment accuracy is required during these tests to ensure more precise radiation therapy for patients [12, 13]. Commissioning tests allow users to understand the adjustment limits of radiotherapy

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equipment, facilitating subsequent QA, QC, and part replacement due to equipment failure [14]. Adjustments to the beam profiles, beam quality, and positions of the MLC and JAW prior to acceptance tests are typically performed exclusively by the vendor. Therefore, users often find it challenging to ascertain feasible tolerance values and adjustment limits. Understanding the acceptable tolerance ranges of linacs by analyzing acceptance test data from multiple facilities is essential to address this challenge. However, to the best of our knowledge, previous studies have evaluated beam matching and representative beam data [15, 16], no study to date has assessed the tolerance range of acceptance tests using data from multiple facilities. This study aims to provide reference levels for acceptance tests, thereby addressing the gaps in prior work relating to unclear adjustment limits as well as differences between junior and experienced personnel. In addition, understanding the adjustment limits of linacs can eliminate excessive demands from users and insufficient adjustments by vendors, thereby promoting the standardization of linac precision.

MATERIALS AND METHODS

The linac acceptance tests included eight TrueBeam, four VitalBeam, and one TrueBeam STx models (Varian Medical Systems, Palo Alto, CA, USA) installed between 2015 and 2024. The acceptance test years for these machines were as follows: two TrueBeam in 2015, one TrueBeam STx in 2017, one TrueBeam in 2018, one VitalBeam and one TrueBeam in 2019, two TrueBeam and two VitalBeam in 2022, one VitalBeam in 2023, and two TrueBeam in 2024. This study focused on dosimetry and mechanical acceptance tests. The study flow is shown in figure 1.

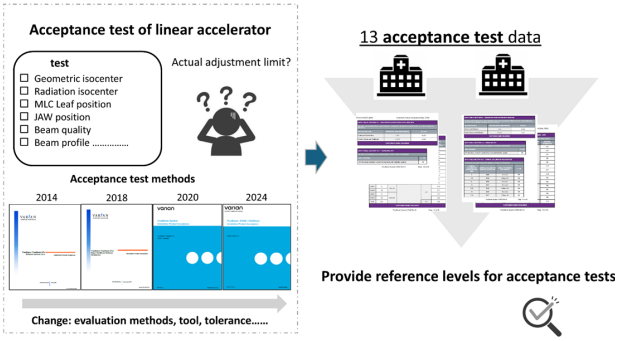


Figure 1. Study flow chart. MLC: multileaf collimator.

Isocenter tuner stand position (~2021)

The geometric isocenter of the stand position, which was located on the hoisting and rigging floor at the time of installation, was evaluated. From 2023, this numerical evaluation of the stand position was excluded from the acceptance tests.

Radiation isocenter with IsoLock (~2022)

The radiation isocenter was evaluated using IsoLock by adjusting the gantry, collimator, and couch with a couch mount assembly and tungsten ball. A total of 63 images were captured at various gantry and collimator angles. The images were analyzed individually, and the specifications were verified using the IsoLock application.

MLC leaf and JAW positional accuracy (~2021)

Prior to 2022, the MLC and JAW positions were visually determined by placing graph paper on the couch at a 100 cm source-to-surface distance and verifying the alignment with a crosshair.

MLC leaf and JAW positional accuracy (~2022)

From 2022, the evaluation method for the MLC leaf and JAW positions changed from graph paper to a machine performance check using an electronic portal imaging device. The MLC leaf position accuracy and repeatability were tested across three plans for banks A and B. In addition, the positional accuracy and parallelism of the JAW were assessed using four plans (X1, X2, Y1, and Y2).

Dose profile and beam quality acceptance testing (~2021)

Prior to 2022, the in-plane and cross-plane dose profiles were measured at a 100 cm source-chamber distance (SCD) and 10 cm depth using a CC13 ionization chamber (IBA Dosimetry, Schwarzenbruck, Germany) and water scanning system. Flatness was assessed by evaluating the maximum dose variation between the minimum and maximum points within the central 80% of the in-plane and cross-plane major axes at a 100 cm SCD and 10 cm depth. In the symmetry acceptance test, the maximum variation in the integrated dose between two corresponding points that were equidistant from the beam centerline within the central 80% of the radial and transverse major axes at a 100 cm SCD and 10 cm depth should not exceed 2.0%.

The beam quality was evaluated by measuring the ionization depths at 90%, 80%, and 50% of the maximum beam intensity at a 100 cm SCD and with a 15 × 15 cm^2 field size using a water phantom.

Dose profile and beam quality acceptance testing (~2022)

From 2022, the profiles were evaluated using an IC Profiler (Sun Nuclear Corporation, Melbourne FL, USA) with a 30 × 30 cm^2 field and solid water buildup. Flatness was measured as the maximum variation in the integrated dose between the minimum and maximum points within the full width at half maximum (FWHM) of the in-plane and cross-plane major axes at a 100 cm SCD and an 85%/2 depth. Symmetry was evaluated as the maximum variation in the integrated dose between any two corresponding points that were equidistant from the beam centerline within the FWHM of the in-plane and

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cross-plane major axes at a 100 cm SCD and an 85%/2 depth. The beam quality was assessed using copper wedges. All depth specifications for the enhanced beam compatibility (EBC) option were accepted if the results met the tolerances listed in the EBC column.

Electron beam quality and profile acceptance testing (~2021)

The ionization depths were set to 90%, 80%, and 50% of the maximum beam intensity using a water phantom at a 100 cm SCD and with a 15 × 15 cm^2 field size for the electron beam quality testing. The tolerance values listed in either the tolerance specification for system without Enhance Beam Conformance option (TOL1) or EBC columns must meet the depth specifications for the Electrons option. The Electrons option was purchased and the tolerance values for the EBC were adjusted for all depth specifications.

For obtaining flatness, the maximum variation in the integrated dose between the minimum and maximum points within the central 80% of the in-plane and cross-plane major axes at a 100 cm SCD and an 85%/2 depth was adjusted to meet the specifications listed in the data table.

For symmetry, the maximum variation in the integrated dose between two corresponding points that were equidistant from the beam centerline within the central 80% of the in-plane and cross-plane major axes at a 100 cm SCD and an 85%/2 depth was adjusted to not exceed 2.0%.

Electron beam quality and profile acceptance testing (~2022)

Flatness was measured as the integrated dose between the minimum and maximum points within the FWHM of the in-plane and cross-plane central axes using an IC Profiler. Symmetry was evaluated by calculating the integrated dose between two corresponding points that were equidistant from the beam centerline within the FWHM areas of the in-plane and cross-plane central axes. For the electron beam quality, the I50 (50% ionization) depth values were measured using an IC Profiler and an aluminum quad-wedge accessory.

Comparison of acceptance test results across facilities

The average, maximum, minimum, and standard deviation (SD) values for each test parameter across facilities were calculated. Deviations between the tolerances and adjustment results were evaluated using box plots.

RESULTS

Table 1 presents the results of the stand position following the geometric isocenter adjustment. The average gantry skew was less than half of the specified tolerance, while the average gantry sag exceeded half of the allowed limit. The radiation isocenter verification, performed using IsoLock, showed minimal SDs for the gantry and collimator among facilities (0.01 mm). However, the SD for the radiation isocenter, including the couch, was larger (0.06 mm).

Table 1. Acceptance test for mechanical and radiation isocenter.

Isocenter tuner stand position			
	Requirement (mm)	**Ave. (min-max)**	**SD**
Gantry skew	±0.10	0.01 (-0.07-0.04)	0.03
Gantry sag	±0.36	0.28 (0.26-0.30)	0.02
Stand position radial	±0.08	0.00 (-0.05-0.05)	0.03
Stand position transverse	±0.08	0.00 (-0.05-0.05)	0.03
Isocenter verification using IsoLock			
	Specification (mm radius)	Ave. (min-max)	SD
Gantry and collimator	≤0.5	0.27 (0.24-0.28)	0.01
Couch, gantry, and collimator	≤0.75	0.57 (0.47-0.68)	0.06

Ave: average, SD: standard deviation.

The results of the acceptance testing for the MLC and JAW positions are shown in table 2 and figure 2. The evaluation of these positions prior to 2021 was challenging owing to reliance on visual assessments using graph paper.

Following 2022, the average MLC maximal leaf offsets (A and B) were below half the tolerance, whereas the SD values were higher than those of the isocenter acceptance tests. The average values for the MLC offset reproducibility were >0.2 mm, whereas the SDs among facilities remained low (0.05).

Table 2. Acceptance test for MLC and JAW positions.

MLC and JAW maximal offset			
Test criteria	**Specification tolerance (mm)**	**Ave. (min-max)**	**SD**
MLC maximal leaves A offset	±1.0	-0.33 (-0.60-0.41)	0.34
MLC maximal leaves B offset	±1.0	-0.30 (-0.76-0.68)	0.59
MLC maximal leaves A offset reproducibility	±0.5	0.36 (0.30-0.42)	0.05
MLC maximal leaves B offset reproducibility	±0.5	0.31 (0.21-0.35)	0.05
JAW X1 maximal offset	±1.0	0.26 (-0.39-0.68)	0.42
JAW X2 maximal offset	±1.0	0.24 (-0.40-0.72)	0.45
JAW Y1 maximal offset	±2.0	-0.21 (-1.08-0.82)	0.71
JAW Y2 maximal offset	±2.0	0.50 (-0.79-1.54)	0.90
JAW parallelism offset			
Test criteria	**Specification tolerance (mm)**	**Ave. (min-max)**	**SD**
JAW X1 maximal parallelism offset	±0.4°	0.02 (-0.02-0.06)	0.04
JAW X2 maximal parallelism offset	±0.4°	-0.01 (-0.06-0.04)	0.05
JAW Y1 maximal parallelism offset	±0.4°	-0.09 (-0.16-0.00)	0.06
JAW Y2 maximal parallelism offset	±0.4°	-0.04 (-0.17-0.15)	0.12

MLC: multileaf collimator, Ave: average, SD: standard deviation.

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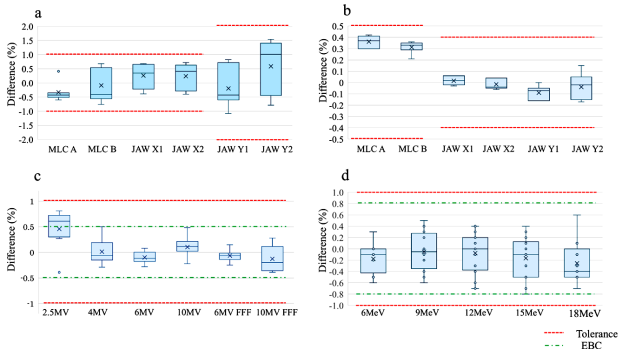


Figure 2. (a) Position for MLC and JAW offsets and **(b)** reproducibility for MLC and JAW offsets; **(c)** photon energy verification; **(d)** electron energy verification. The red line indicates the normal tolerance and the green line indicates the EBC tolerance. MLC: multileaf collimator, EBC: enhanced beam compatibility.

The average value and SD for the JAW maximal offset among facilities were >0.2 mm and 0.4 mm, respectively, with the Y JAWs exhibiting greater deviations than the X JAWs (maximum X1: 0.72 mm, Y2: 1.52 mm). The maximal parallel offset of the JAW was <0.2°.

Table 3 and figure 2(c) and (d) display the beam quality of the photon and electron beams. All photon beams were within the EBC tolerance (≦±0.5), with the largest SD observed for 2.5 MV image matching. The average value for the electron beams was within ±0.04, and the values of all facilities were below the EBC threshold. All electron beam qualities were within the EBC tolerance and the SD for all energies was <0.05.

Table 3. Photon and electron energy verification.

Photon energy verification					
Energy (MV)	Photon D10			Ave. (min-max)	SD
	Spec. (%)	Tolerance (%)			
		TOL1	EBC		
2.5	52	±1	±0.5	0.46 (-0.39-0.81)	0.38
4	63			0.01 (-0.29-0.50)	0.26
6	67.2			-0.10 (-0.28-0.08)	0.11
10	74.1			0.10 (-0.22-0.48)	0.17
6FFF	64.3			-0.06 (-0.25-0.15)	0.11
10FFF	71.8			-0.05 (-0.39-0.30)	0.27
Electron energy verification					
Energy (MeV)	I50 depth			Ave. (min-max)	SD
	Spec. (cm)	Tolerance (cm)			
		TOL1	EBC		
6	2.32	±0.1	±0.07 (6e&9e)	-0.02 (-0.06-0.03)	0.02
9	3.52			-0.01 (-0.06-0.05)	0.03
12	4.91		±0.08 (12e-22e)	-0.01 (-0.07-0.04)	0.04
15	6.19			-0.02 (-0.08-0.04)	0.04
18	7.41			-0.03 (-0.07-0.06)	0.04

D10:10 cm depth, Spec.: specification, TOL1: tolerance specification for system without Enhance Beam Conformance option, EBC: Optional Enhance Beam Conformance tolerancw specification, Ave: average, SD: standard deviation, FFF: flattening filter-free, I50: 50% ionization.

The photon flatness and symmetry results are presented in figure 3 and table 4. The flatness of both the in-line and cross-line directions was more than half of the required value, and the SD for the flatness was smaller than that for the symmetry in both directions.

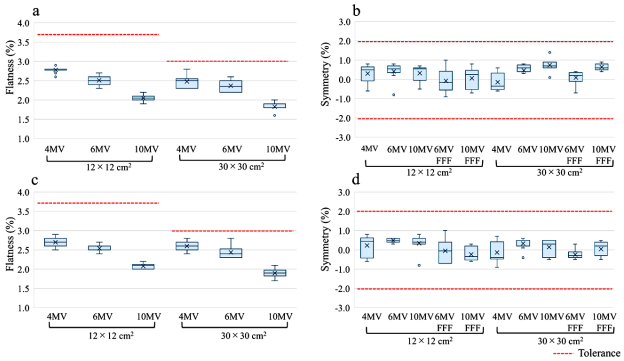


Figure 3. Relationship between tolerance and photon flatness and symmetry among facilities: **(a)** and **(b)** in-line measurements; **(c)** and **(d)** cross-line measurements. The red line indicates the tolerance. FFF: flattening filter-free.

Table 4. Acceptance test for photon flatness and symmetry.

Photon flatness and symmetry						
Energy (MV)	Field size (cm^2)	Flatness requirement (%)	In-line ave. (min-max)	SD	Cross-line ave. (min-max)	SD
4	12 × 12	±3.7	2.74 (2.35-2.70)	0.15	2.70 (2.50-2.89)	0.13
6			2.49 (2.27-2.70)	0.13	2.54 (2.40-2.70)	0.13
10			2.03 (1.79-2.20)	0.11	2.08 (2.00-2.20)	0.09
4	30 × 30	±3.0	2.40 (2.00-2.80)	0.22	2.60 (2.40-2.80)	0.20
6			2.26 (1.40-2.60)	0.33	2.44 (2.30-2.80)	0.32
10			1.81 (1.60-2.00)	0.14	1.96 (1.70-2.60)	0.25
Energy (MV)	Field size (cm^2)	Symmetry requirement (%)	In-line ave. (min-max)	SD	Cross-line ave. (min-max)	SD
4	12 × 12	≤2	0.31 (-0.60-0.80)	0.50	0.23 (-0.60-0.80)	0.54
6			0.42 (-0.80-0.80)	0.44	0.49 (0.30-0.60)	0.11
10			0.32 (-0.50-0.70)	0.44	0.34 (-0.80-0.80)	0.43
4	30 × 30	≤2	-0.07 (-0.90-1.00)	0.62	-0.05 (-0.70-1.00)	0.60
6			0.06 (-0.70-0.80)	0.54	-0.23 (-0.60-0.30)	0.34
10			-0.14 (-0.60-0.60)	0.45	-0.13 (-0.90-0.70)	0.55
6FFF	10 × 10	≤2	0.47 (-0.80-0.80)	0.48	0.31 (-0.40-0.60)	0.31
10FFF			0.74 (0.10-1.40)	0.37	0.08 (-0.50-0.50)	0.42
6FFF	30 × 30		0.10 (-0.70-0.40)	0.38	-0.21 (-0.40-0.30)	0.27
10FFF			0.64 (0.40-0.90)	0.17	-0.03 (-0.50-0.40)	0.40
2.5		≤3	0.37 (-1.00-0.90)	0.66	-0.02 (-1.10-1.60)	0.98

Ave: average, SD: standard deviation, FFF: flattening filter-free.

Table 5 and figure 4 presents the flatness and symmetry of the electron beams. The average values for both the in-line and cross-line flatness were less than half of the required values, except for the 6 MeV for the 15 × 15 cm^2 field size. The SD of the flatness was smaller than that of the symmetry for both the

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in-line and cross-line measurements.

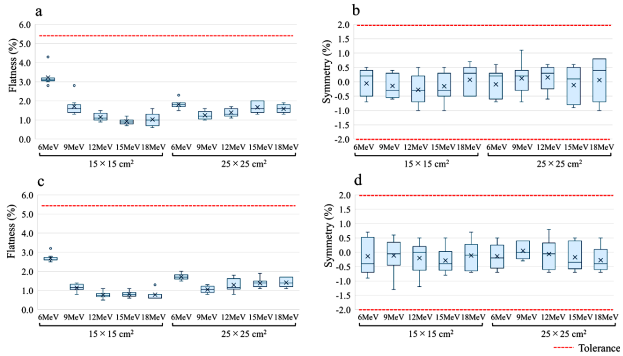


Figure 4. Relationship among tolerance, electron flatness, and symmetry across facilities: **(a)** and **(b)** in-line measurements; **(c)** and **(d)** cross-line measurements. The red line indicates the tolerance. FFF: flattening filter-free.

Table 5. Acceptance test for electron flatness and symmetry.

	Electron flatness and symmetry					
Energy (MeV)	**Field size (cm^2)**	**Flatness req. (%)**	**In-line ave. (min–max)**	**SD**	**Cross-line ave. (min-max)**	**SD**
6	25 × 25 applicator	±5.4 (±6.0 for 6e)	1.87 (1.50-2.40)	0.28	1.72 (1.50-2.00)	0.15
9			1.23 (1.00-1.60)	0.21	1.05 (0.80-1.30)	0.18
12			1.41 (1.10-1.70)	0.21	1.29 (0.80-1.80)	0.33
15			1.68 (1.30-2.00)	0.27	1.43 (1.10-1.90)	0.27
18			1.56 (1.30-1.90)	0.21	1.41 (1.10-1.70)	0.21
6	15 × 15 applicator	±5.4 (±6.0 for 6e)	3.21 (2.80-4.30)	0.40	2.69 (2.50-3.20)	0.20
9			1.71 (1.30-2.80)	0.43	1.15 (0.80-1.40)	0.20
12			1.14 (0.90-1.50)	0.20	0.77 (0.50-1.10)	0.18
15			0.99 (0.70-1.40)	0.22	0.81 (0.60-1.10)	0.16
18			1.05 (0.60-1.60)	0.34	0.79 (0.60-1.30)	0.23
Energy (MeV)	**Field size (cm^2)**	**Symmetry req. (%)**	**Ave. (min-max)**	**SD**	**Ave. (min-max)**	**SD**
6	25 × 25 applicator	≤2	0.08 (-0.70-1.60)	0.73	-0.14 (-0.70-0.50)	0.44
9			0.17 (-0.70-1.10)	0.51	0.05 (-0.30-0.40)	0.30
12			0.08 (-0.60-0.60)	0.49	-0.06 (-0.70-0.80)	0.50
15			0.01 (-0.90-0.90)	0.27	-0.18 (-0.70-0.50)	0.48
18			0.20 (-1.00-1.20)	0.82	0.31 (-0.40-0.80)	0.35
6	15 × 15 applicator	≤2	-0.10 (-0.70-0.50)	0.48	-0.14 (-0.90-0.70)	0.62
9			-0.21 (-0.80-0.40)	0.45	-0.11 (-1.30-0.60)	0.58
12			-0.34 (-1.00-0.50)	0.51	-0.20 (-1.20-0.50)	0.53
15			-0.26 (-1.00-0.50)	0.57	-0.29 (-0.80-0.50)	0.42
18			-0.03 (-0.70-0.70)	0.58	-0.11 (-0.70-0.70)	0.51

Req: required, Ave: average, SD: standard deviation.

DISCUSSION

This study summarizes the results of 13 linac acceptance tests. The geometric and radiation isocenters of the gantry and collimator were closely aligned (≦ 0.3 mm), with a maximum inter-facility variation of ≦0.1 mm. These differences are attributed to sagging caused by the weight of the gantry head; however, the minimal variability between facilities indicates a high level of reproducibility in installation [17-19]. The maximum inter-facility variation in the radiation isocenter of the couch, gantry, and collimator was ≧0.2 mm. Such deviations may introduce systematic differences in dose distribution during high-precision radiation therapy; hence, minimizing these discrepancies is essential [19].

The average and SD of the maximum MLC leaf offset among facilities were high (approximately 0.3 mm) compared with the reproducibility of the MLC maximal leaf offset. This variability likely stems from onsite adjustments of the MLC gap and carriage position by service vendors following shipment from the factory [20]. Consequently, users should recognize that MLC positioning varies across facilities and verify their systems using methods such as split-field or strip tests [21, 22]. These inter-facility differences indicate that the MLC leaf offset and transmission parameters that are registered in the treatment planning system of one facility cannot be directly applied to another [20]. In the future, standardizing MLC positioning could eliminate the need for commissioning these parameters.

The SD of the Y JAW maximum offset was larger (>0.7 mm) than that of the X JAW. This discrepancy arises from the reliance of the vendor on visual adjustments using graph paper and the light field at the 1 cm and 19 cm JAW positions. Differences in individual vendor techniques and the upper positioning of the Y JAW relative to the X JAW contribute to challenges in achieving uniform adjustments and may result in a suboptimal penumbra [23-25]. Consequently, the JAW adjustments that are performed during acceptance testing are prone to variability within specified requirements, necessitating thorough validation by users, similar to the process for the MLC.

The photon and electron beam quality values were within the tolerance range of the EBC system and were close to the adjustment limits. Facilities that do not use the EBC option can benefit from these high-quality adjustments, as beam quality readjustments necessitated by equipment failure can be facilitated by referencing the acceptance test tolerance values [26]. For flattening filter-free (FFF) beam quality adjustments in the Varian system, the D10 difference between the flattening filter (FF) and FFF beams was >3%, reflecting insufficient matched energy [27]. Therefore, users should account for differences in the

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FF and FFF radiation quality in clinical applications.

The SD of the symmetry across facilities was larger than that of the flatness. This variability is likely associated with the beam alignment adjustments of the vendors at individual facilities [28]. The average flatness values indicated that the photons exceeded half of the required tolerance levels, whereas the electrons were below half. Adjusting the photon flatness may be more challenging than adjusting the electron flatness, possibly owing to deviations of the photon beam center from the center of the FF. In addition, the greater symmetry values for the FFF beams than for the FF beams likely reflect the prioritization of beam alignment error reduction.

The limitation of this study is that the age and years of experience of vendors were not investigated. Although designating specific vendors is challenging, we consider that the findings of this study provide reference data that may help mitigate variations in technical proficiency across vendors. In addition, the primary limitation of this study is the lack of evaluation of acceptance tests for imaging components. Future studies that incorporate imaging evaluations can provide more comprehensive and actionable insights.

This study provides a valuable reference for actual tolerance levels during the commissioning of linac equipment. Although previous reports have addressed commissioning and regular QA data, this study offers specific tolerance values for new linac installations [29-31]. Notably, many reported adjustment values were below half of the tolerance levels, suggesting that users can operate the linac equipment confidently by gradually adjusting the functional test values closer to these thresholds.

CONCLUSION

This study has summarized the results of acceptance tests of Varian linac systems across 13 facilities. The findings indicated minimal variation in isocenter adjustments when using software across the facilities. However, the SD for manual adjustments, including the MLCs, JAWs, beam quality, and profiles, were notably large. These results provide a reference for new linac facilities, aiding in the standardization of radiation therapy equipment operations.

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