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Beam Matching Assessment of Two Medical Linear Accelerators Using Flatness and Symmetry Profile Measurements from Routine Quality Assurance

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ABSTRACT

Beam matching of linear accelerators ensures interchangeable treatment delivery across machines and supports clinical flexibility. This study evaluates beam matching of two Elekta Synergy Platform linacs using routine quality-assurance (QA) flatness and symmetry profiles collected in 2024–2025. Routine profile scans were acquired with a PTW Semiflex ionization chamber (0.125 cm^3) in a 3D water phantom at SSD 90 cm, 10 cm depth, and a 10×10 cm^2 field. Flatness and symmetry were calculated for in-plane and cross-plane profiles across periodic QA sessions and compared between Linac 2 and Linac 3 using descriptive statistics to assess inter-machine differences and compliance with QA tolerances. Mean flatness (in-plane) was 103.91% (SD 0.27) for Linac 3 and 104.26% (SD 0.64) for Linac 2; cross-plane flatness means were 104.89% (SD 0.23) and 105.04% (SD 0.19), respectively. Symmetry means were closely matched: in-plane 100.67% vs 100.55% (mean $\Delta \approx 0.11\%$) and cross-plane 100.52% vs 100.48% (mean $\Delta \approx 0.03\%$). Typical inter-machine absolute differences across metrics ranged 0.23–0.45%. One isolated in-plane flatness excursion (~2.04%) was observed and flagged for follow-up. Longitudinal routine QA shows the two Elekta Synergy linacs are well matched for routine 3DCRT and many IMRT/VMAT workflows, with low inter-machine variability. Continued periodic verification and prompt investigation of outliers are recommended, and stricter criteria should apply for stereotactic treatments

Keywords: Beam Matched Linacs, Routine QA, Flatness Profile, Symmetry Profile

INTRODUCTION

The use of medical linear accelerators (Linacs) in radiotherapy has become a cornerstone in the treatment of cancer due to their capability to deliver highly conformal megavoltage photon beams with high precision. To ensure consistent and safe treatment delivery, robust quality assurance (QA) programs are essential. These programs monitor critical dosimetric parameters, including beam flatness and symmetry, which describe lateral dose uniformity and balance in the radiation field, respectively - key indicators of beam quality that directly influence dose homogeneity in clinical plans (*1*).

Beam matching refers to the process of aligning the dosimetric characteristics of multiple Linacs so that a patient's treatment plan can be delivered interchangeably across machines without reoptimization or replanning (*2*). This capability is increasingly important in institutions operating more than one Linac, as it enhances clinical flexibility and minimizes delays in patient care. Flatness and symmetry profiles serve as fundamental metrics for evaluating beam match quality, as variations in these parameters can lead to differences in dose distribution across machines (*3*).

Current QA guidelines emphasize the routine monitoring of beam flatness and symmetry as part of performance tests to maintain Linac function within clinically acceptable limits. These parameters are routinely assessed through periodic QA measurement protocols that aim to detect deviations from baseline performance, thereby ensuring that the physical characteristics of the beam remain stable over time (*1*)(*4*).

Recent studies have demonstrated that longitudinal analysis of QA data can provide valuable insights into both machine stability and inter-machine consistency (*5*). For instance, clinical analyses of flatness and symmetry measurements over extended periods indicate that maintaining these metrics within tolerance supports reliable beam delivery and quality treatment outcomes (*6*).

Despite the importance of these observations, the use of actual routine QA profile data over long-time frames for systematic beam matching assessment has been relatively underreported in the literature, particularly in settings where multiple matched Linacs are used in daily clinical practice. A more detailed examination of long-term QA measurements may therefore fill this gap by validating the consistency of beam characteristics and informing QA protocols (*7*).

Accordingly, the aim of this study is to assess the beam matching performance of two medical linear accelerators by analyzing flatness and symmetry profile measurements obtained from routine quality assurance over a one-year period. Through longitudinal QA data analysis, this study evaluates the stability of beam metrics, inter-machine consistency, and compliance with established QA recommendations, thereby demonstrating the utility of routine QA data in beam matching evaluation.

MATERIALS & METHODS

This study was conducted using two medical linear accelerators (Linacs) installed at Dr. Sardjito General Hospital, Yogyakarta, Indonesia. Both units were Elekta Synergy Platform systems configured with 6 MV flattened photon beams and had undergone beam matching during commissioning. The First Linac is Synergy Platform Multi Energy as a Reference Linac (hereby L2 / Linac 2) and The Second Linac is Synergy Platform Single Energy Photon as a Tested Beam Matched Linac (hereby L3 / Linac 3). The matched beam configuration was clinically implemented to support interchangeable patient treatments across both Linacs. The two Linacs were operated under routine clinical conditions throughout the study period, and no major hardware modifications were performed during data acquisition.

Beam profile measurements were performed using a PTW Semiflex ionization chamber with an active volume of 0.125 cm^3 (PTW-Freiburg, Germany). The detector was selected due to its widespread clinical use, favorable spatial resolution, and suitability for beam profile measurements in megavoltage photon beams under reference field conditions (*8*).

A PTW three-dimensional (3D) water phantom system was used to acquire beam profile data. The water phantom provided accurate detector positioning and reproducible scanning geometry, enabling precise lateral dose measurements required for flatness and symmetry evaluation. The dosimetry system was calibrated according to the manufacturer's recommendations and institutional QA procedures prior to data acquisition (*9*).

All measurements were conducted using a standardized reference geometry. The source-to-surface distance (SSD) was set to 90 cm, and the ionization chamber was positioned at a depth of 10 cm in water, corresponding to a clinically relevant measurement depth for beam profile evaluation. The radiation field size was defined as 10 × 10 cm² at the water surface, which is the conventional reference field used in routine QA and beam matching assessments.

The detector was aligned along the central axis of the beam prior to profile scanning to ensure accurate symmetry evaluation. Beam profiles were measured in both in-plane and cross-plane directions. Environmental conditions, including room temperature and pressure, were monitored and appropriate corrections were applied according to standard dosimetric practice.

Beam profile data were obtained retrospectively from routine quality assurance (QA) measurements performed over a two-year period (2024 and 2025). QA measurements were conducted at regular intervals in accordance with institutional QA protocols and current international recommendations for linear accelerator performance testing.

The use of routine QA data allows evaluation of beam matching performance under actual clinical operating conditions, reflecting realistic machine behavior over time rather than isolated commissioning measurements.

Beam profile analysis focused on flatness and symmetry, which are key indicators of lateral dose uniformity and beam balance (*10*). Flatness was evaluated as the maximum deviation of the dose distribution from the mean dose within the central region of the radiation field, excluding the penumbra, and expressed as a percentage. Symmetry was defined as the maximum relative dose difference between corresponding points equidistant from the central axis along a given profile direction.

The evaluation methods and acceptance criteria were based on current quality assurance recommendations for medical linear accelerators, which emphasize periodic verification of beam profile stability to ensure consistent clinical performance (*1*).

For each Linac, flatness and symmetry values were calculated for all QA measurement sessions. Descriptive statistical analysis was performed, including determination of the mean, standard deviation, and maximum observed deviation for each parameter (*11*). Beam matching performance was assessed by comparing flatness and symmetry values between the two Linacs and evaluating the magnitude of inter-machine differences (*3*).

Compliance with recommended QA tolerances was assessed to determine whether the matched beams remained within clinically acceptable limits throughout the study period. All data analysis was performed using standard spreadsheet and statistical software.

RESULT

Paired profile measurements (Linac 3 vs Linac 2) were extracted from routine QA records and analyzed for flatness and symmetry in both the in-plane and cross-plane directions. Using paired routine QA data for longitudinal assessment is consistent with recent guidance advocating trend-based performance monitoring to detect episodic deviations that single-point commissioning may miss (*1*)(*12*).

a. Flatness In-plane Direction

In-plane flatness means were 103.91% (Linac 3) and 104.26% (Linac 2) with respective SDs of 0.27% and 0.64%. The mean absolute inter-machine difference was 0.45%, the minimum observed absolute difference was 0.06% and the maximum observed absolute difference was 2.04% from Table 1.

The small average inter-machine difference (0.45%) indicates generally good matching of the in-plane profile shape between the two Elekta Synergy Platform units under routine operation. This magnitude of agreement is comparable to recent multi-center beam-matching reports that found sub-percent to low-percent typical differences after commissioning and routine QA (3). However, the isolated in-plane outlier (mean = 2.04%) is clinically important: episodic excursions above institutional tolerances have been shown in longitudinal QA studies to represent either transient machine events or measurement/recording issues and therefore require targeted investigation (*1*)(*12*). Possible root causes include temporary steering or flattening-filter alignment issues, detector/phantom mispositioning (*1*)(13). Per AAPM recommendations, isolated exceedances should prompt immediate re-measurement and diagnostic checks rather than being dismissed as single outliers (*1*).

Table 1. Comparison Flatness – In-plane Direction

Linac 3		**Linac 2**		**Deviation Abs.**
Month	**Flatness (%)**	**Month**	**Flatness (%)**	
4TH-24	104,27	4TH-24	104,21	0,06%
8TH-24	103,71	8TH-24	103,81	0,10%
12TH-24	103,81	12TH-24	103,93	0,12%
4TH-25	103,85	4TH-25	103,97	0,12%
8TH-25	103,55	8TH-25	105,66	2,04%
12TH-25	104,27	12TH-25	103,98	0,28%
Mean	103,91	Mean	104,26	0,45%
STDEV	0,27	STDEV	0,64	

b. Flatness Cross-plane Direction

Cross-plane flatness means were 104.89% (Linac 3) and 105.04% (Linac 2) with SDs 0.23% and 0.19% respectively; mean absolute inter-machine difference was 0.24%, minimum was 0.09% and maximum was 0.46% from Table 2.

Cross-plane agreement is excellent and shows no outliers, supporting consistent machine behavior in that axis. The directional contrast (an in-plane outlier vs stable cross-plane results) is consistent with prior reports that observed axis-dependent variations after matching, often due to steering subtleties or mechanical factors affecting one axis more than the other (*13*). The robust cross-plane agreement increases confidence that global monitor chamber behavior and overall machine stability are satisfactory, and that the in-plane anomaly is likely localized (machine- or measurement-specific) rather than reflecting a global failure (*3*).

Table 2. Comparison Flatness – Cross-plane Direction

Linac 3		**Linac 2**		**Deviation Abs.**
Month	**Flatness (%)**	**Month**	**Flatness (%)**	
4TH-24	105,16	4TH-24	105,07	0,09%
8TH-24	104,79	8TH-24	104,75	0,04%
12TH-24	105,18	12TH-24	104,99	0,18%
4TH-25	104,50	4TH-25	104,93	0,41%
8TH-25	104,88	8TH-25	105,36	0,46%
12TH-25	104,85	12TH-25	105,12	0,26%
Mean	104,89	Mean	105,04	0,24%
STDEV	0,23	STDEV	0,19	

c. Symmetry – In-plane and Cross-plane Direction

Symmetry values were tightly matched in Table 3. For in-plane directions, means 100.67% from Linac 3 versus 100.55% from Linac 2 with mean 0.23% (mean min. 0.08% and max. 0.38%). From Table 4, cross-plane directions mean 100.52% (Linac 3) vs 100.48% (Linac 2) with mean 0.24% (which mean min. 0.04% and max. 0.42%).

Table 3. Comparison Symmetry – In-plane Direction

Linac 3		**Linac 2**		**Deviation Abs.**
Month	**Symmetry (%)**	**Month**	**Symmetry (%)**	
4TH-24	100,53	4TH-24	100,61	0,08%
8TH-24	100,64	8TH-24	100,50	0,14%

12^{TH}-24	100,82	12^{TH}-24	100,66	0,16%
4^{TH}-25	100,72	4^{TH}-25	100,37	0,35%
8^{TH}-25	100,38	8^{TH}-25	100,64	0,26%
12^{TH}-25	100,92	12^{TH}-25	100,54	0,38%
Mean	100,67	Mean	100,55	0,23%
STDEV	0,18	STDEV	0,10	

The low inter-machine symmetry differences indicate consistent beam balance between the matched Linacs and suggest that the monitor chamber and gross steering are stable across the sample. Symmetry is a sensitive detector of steering imbalance; consistent symmetry results across time are congruent with published findings that symmetry monitoring is a useful, reproducible feature of QA streams for matched units (*14*). The combined profile results (flatness and symmetry) therefore support that the machines are well matched overall while underscoring the need to investigate isolated profile shape deviations.

Table 4. Comparison Symmetry – Cross-plane Direction

Linac 3		**Linac 2**		**Deviation Abs.**
Month	**Symmetry (%)**	**Month**	**Symmetry (%)**	
4^{TH}-24	100,59	4^{TH}-24	100,55	0,04%
8^{TH}-24	100,36	8^{TH}-24	100,29	0,07%
12^{TH}-24	100,86	12^{TH}-24	100,45	0,41%
4^{TH}-25	100,57	4^{TH}-25	100,27	0,30%
8^{TH}-25	100,50	8^{TH}-25	100,70	0,20%
12^{TH}-25	100,22	12^{TH}-25	100,64	0,42%
Mean	100,52	Mean	100,48	0,24%
STDEV	0,20	STDEV	0,16	

d. Beam matching performance and clinical implications.

Across the four evaluated profile metrics, typical inter-machine absolute differences were small (mean Δ 0.23–0.45%). These values align with contemporary beam-matching experiences that report sub-percent to low-percent inter-machine variations after commissioning and ongoing QA (*3*)(*4*). The single in-plane flatness exceedance (~2.04%) does not negate the overall finding of good matching but does highlight the importance of longitudinal trend analysis: repeated QA sampling and trend analytics can reveal episodic deviations that would be missed by single-time-point commissioning (*1*)(*12*).

DISCUSSION

The present study demonstrates that the two Elekta Synergy Platform linear accelerators achieved a high level of dosimetric agreement following beam matching, particularly in terms of beam flatness and symmetry at a depth of 10 cm and an SSD of 100 cm. The observed inter-machine deviations were predominantly within ±1%, indicating clinically acceptable equivalence for routine radiotherapy techniques. Similar levels of agreement among beam-matched linacs have been reported in recent multi-institutional studies, which support patient interchangeability without the need for re-planning in conventional 3DCRT, IMRT, and VMAT workflows (*15*)(*16*).

The importance of longitudinal quality assurance is underscored by the detection of an isolated outlier exceeding 2% in the in-plane direction. Although overall beam characteristics remained stable, such episodic deviations emphasize that single-time-point commissioning measurements may not fully capture temporal beam variations. Subashi et al. (*12*) demonstrated that trend-based monitoring of flatness and symmetry metrics is essential for identifying gradual beam steering drifts or transient mechanical instabilities that may otherwise remain undetected in routine QA programs.

Axis-dependent variations observed in this study, where larger deviations were noted in the in-plane direction compared to the cross-plane direction, are consistent with findings reported in previous investigations. These variations may be attributed to focal spot positioning, steering coil calibration, or subtle asymmetries in flattening filter alignment. Papajani et al. (*13*) reported that flatness and symmetry values are sensitive to both field size and depth, highlighting the need for standardized measurement conditions and careful detector alignment when comparing beam profiles across multiple linacs.

While the agreement achieved in this study is sufficient for routine clinical treatments, recent literature cautions that beam-matching tolerances acceptable for conventional fractionation may not be directly applicable to stereotactic techniques. For SRS and SBRT, stricter dosimetric criteria and additional verification steps—such as small-field output factor validation, high-resolution MLC performance assessment, and tighter gamma analysis thresholds—are recommended prior to allowing distributive delivery across beam-matched linacs (*17*)(*16*). Therefore, although the linacs evaluated in this work are suitable for general clinical interchangeability, supplementary QA measures should be implemented for high-precision stereotactic applications (*18*).

Recent advances in automated QA and EPID-based dosimetry provide valuable tools for enhancing beam-matching verification. Portal dosimetry and three-dimensional gamma analysis using patient-specific treatment plans have been shown to improve sensitivity to subtle inter-machine differences and offer clinically relevant validation beyond conventional water phantom measurements (*19*). Incorporating these methods into routine QA workflows may facilitate early detection of deviations and improve long-term beam consistency.

Overall, the findings of this study, supported by contemporary literature, confirm that effective beam matching between linear accelerators can be achieved and maintained through systematic QA and longitudinal monitoring. Continued adoption of advanced QA technologies and the application of stricter criteria for specialized treatments will further enhance the safety, flexibility, and efficiency of multi-linac radiotherapy operations.

CONCLUSION

This study demonstrates that two Elekta Synergy Platform linear accelerators exhibit overall good beam matching performance based on routine QA flatness and symmetry profile measurements. Mean inter-machine differences for all evaluated parameters were below 0.5%, and all symmetry measurements remained within 1%, indicating stable beam balance and consistent steering. An isolated in-plane flatness deviation exceeding 2% was identified, highlighting the value of longitudinal QA data in detecting episodic variations that may be missed during commissioning. These results support clinical interchangeability of the two Linacs for routine radiotherapy, provided that periodic verification and prompt investigation of outliers are maintained to ensure sustained dosimetric consistency.

Declaration by Authors

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