Radiation Protection Dosimetry, 2023, **199(4)**, 347–355
https://doi.org/10.1093/rpd/ncac285
Advance access publication date 2 January 2023
Paper

OXFORD

Beam matching evaluation of two similar linear accelerators

Soroush Sistani[1], Hamidreza Babaeifar[1], Daryoush Khoramian[1,*], Mahmud Naraqi Arani[1], Mostafa Sarvizadeh[1], Faraz Kalantari[2] and Ali Ebrahimi[1]

[1]Department of Medical Physics, The Advocate Center for Clinical Research, Ayatollah Yasrebi Hospital, Kashan 8715973455, Iran
[2]Department of Radiation Oncology, University of Arkansas for Medical Sciences, Little Rock 72205, United States

*Corresponding author: Daryoushkhoramian@gmail.com

Abstract

To evaluate the beam-matching of two Siemens Primus medical linear accelerators (Linacs), the output factor ($S_{c,p}$), wedge factor, quality index ($TPR_{20/10}$), percentage depth dose (PDD) and beam profiles were compared for 6 and 15 MV photon beams. The output factor, the PDD and the beam profile for electron beam compared for 5, 7, 8, 10 and 12 MeV electron beams. The gamma (γ) analysis of 2 mm/2% and 3 mm/3% was performed. According to the measurements, it can be said that 6 MV photon beams in all field sizes (except 4×4 cm^2) are beam matched. For 15 MV, although the PDDs were matched in all field sizes (except 4×4 cm^2) for both 2 mm/2% and 3 mm/3% γ criteria, beam profiles in field sizes larger than 10×10 cm^2 for 3 mm/3% and in field sizes larger than 8×8 cm^2 for 2 mm/2% were not matched. The electron beams in all applicator sizes (except 5×5 cm^2 applicator) pass the acceptance γ criteria of 3 mm/3% ($\gamma < 1$). Electron beams do not fulfill beam matched in case of the acceptance γ criteria of 2 mm/2%.

Background

Radiotherapy plays an important role in the treatment of a wide range of cancers. About 50% of cancer patients receive radiotherapy during their treatment courses[1, 2]. The goal of radiation therapy is to deliver a prescribed dose to a target volume precisely while minimizing the dose to the surrounding normal tissues[3]. Only a 5% difference between the prescribed dose and the delivered dose may results in about 10–20% in tumor control probability (TCP) and 20–30% in normal tissue complication probability (NTCP)[4]. Such differences can be in the dose calculation phase and/or in the dose delivery phase.

One of the major issues that radiotherapy centers have faced is machine downtime, which can be due to machine breakdown or service time. It imposes treatment interruptions on the patient treatment, which mandates compensatory treatments. Uncompensated interruptions to treatment results in the prolongation of the treatment period and may increase the risk of local recurrence[5].

One way to avoid prolongation of overall treatment time is transferring the patient to a second machine if available[5]. This can be done when the radiotherapy center has beam-matched linear accelerators (Linacs). In this case, patients can be easily transferred between Linacs with minimum effort and without the need of modifying the treatment plan[3, 5]. Beam-match machines have identical dosimetric characteristics[6] including depth dose curves and beam profiles[7].

There are two Siemens Primus Linacs in our center commissioned and installed with a time difference of 1 y. Two linacs were commissioned separately, and no dosimetric comparison has been made between them. Also, two machines were modeled in the treatment planning system (TPS) separately and treatment planning is performed separately according to the machine to be selected. The goal of this study is to evaluate the level of beam matching by comparing dosimetric parameters including beam profiles, percentage depth dose curves and absolute dosimetry values. For comparison, γ was used to quantify the differences between the dose distributions of two linacs[8].

Material and methods

Two Siemens Primus linacs (Siemens Primus, Siemens Medical Systems, Concord, CA, USA) were installed in our department with a time interval of 1 y. Both linacs are capable to generate photon beams with nominal energies of 6 and 15 MV five electron beams with nominal energies of 5, 7, 8, 10 and 12 MeV.

Received: November 28, 2021. **Revised:** September 30, 2022. **Editorial decision:** November 24, 2022. **Accepted:** November 24, 2022

To evaluate the beam matching, relative and absolute dosimetric parameters including percentage depth dose (PDD) and beam profiles, output factor, and wedge factors were measured for both photon beams and the PDDs, beam profiles and the output factor for 5, 8 and 12 MeV electron beams that were commonly used in the clinic. It should be noted that both linacs fulfilled Siemens acceptance test protocols (ATPs) according to company criteria.

Measurements

Both available photon energies of 6 and 15 MV and the most clinically used electron energies of 5, 8 and 12 MeV used for three-dimensional (3D) conformal radiotherapy (3DCRT) were compared to evaluate the beam matching.

The PDDs and profiles (in-plane and cross-plane) for both photon beams were measured for five field sizes 4×4, 8×8, 10×10, 15×15, and 35×35 cm^2. The PDD curves for photon beams were measured from the depth of 30 cm to the phantom surface at source to surface distance (SSD) of 90 cm. The choice of this value of SSD is because the treatment planning system used in our clinic suggests 90 cm of SSD data for modeling in the data entry stage. Each PDD was generated by normalizing the depth dose curve to its corresponding maximum dose. Beam profiles were measured in above-mentioned field sizes at depth of 10 cm.

Along with profile measurements output factors ($S_{c,p}$), and tissue phantom ratio (TPR) (quality index) were measured and compared between two Linacs for photon beams.

Also, wedge factors for all hard wedges were measured and compared between two Linacs. The wedge factor defines as the ratio of dose at a suitable point in phantom with and without the hard wedge. The point of interest in our study was depth of 10 cm.

For electron beams, the depth dose curves were measured with two cone sizes of 10×10 and 20×20 cm^2 from the depth of 10 cm to the phantom surface. Each PDD was generated by normalizing the depth dose curve to its corresponding maximum dose. The PDD curves were measured at SSD of 100 cm.

For electron beams in-plane and cross-plane curves were measured at the depth of R_{100}, which vary with energy and cone sizes. Details of measurements are summarized in Table 1. The beam profiles were measured in 100 cm of the SSD.

The absolute measurements were performed according to the TRS 398 protocol by applying all correction factors. The photon and electron on both Linacs were delivered with dose rates of 200 and 300 MU/min, respectively. Details on point measurements are summarized in Table 2.

Phantom and dosemeters

All absolute photon and electron measurements were carried out using a waterproof 0.6 cm^3 Farmer ionization chamber (PTW type 30013) and Advanced Markus ionization chamber (PTW type 34045) with an active volume of 0.02 cm^3, respectively.

All profile measurements were performed by using a Semiflex ionization chamber (PTW type 31010) with active volume of 0.125 cm^3. All measurements were performed in PTW-MP3 water phantom with the dimensions of $50 \times 50 \times 60$ cm^3. Mephysto mc^2 software (PTW, Freiburg, Germany Version 3.3) was used to navigate detectors and analyze the scanned PDDs and beam profiles.

Before starting the measurements, all the mechanical checks were performed to reduce uncertainties. We also used the module CenterCheck (Mephysto V 3.3) to center the detector precisely with respect to the central axis (CAX) of the beam.

Gamma index calculation

One of the best methods for quantitative evaluation of planning and radiation dose in radiotherapy is based on the γ calculation developed by Low *et al.*[(9)]. The γ index combines dose difference ΔD and distance to agreement (DTA) in one formalism and overcomes the disadvantages of ΔD and DTA.

In this study we used the γ analysis method to compare one-dimensional PDD and profile curves. Each point in the PDD and beam profile curves consist of two characteristics: dose value and location. The comparison of the reference and evaluated curves can be done based on the ΔD and/or based on the distance to the agreement (DTA)[(4)]. Dose difference is defined as the dose difference between the dose at reference point $D(r_R)$ and dose at the evaluated point $D(r_E)$[(10)]:

$$\Delta D\left(r_R, r_E\right) = D_E\left(r_E\right) - D_R\left(r_R\right)$$

Low *et al.*[(9)] defined the DTA as “the closest location in the evaluated dose distribution with the same dose as the point in the reference distribution”. The γ index combines ΔD and DTA in one formalism and overcomes disadvantages of ΔD and DTA in steep dose gradient and low-dose gradient regions. The γ is finding the minimum amount of the below value[(10)]:

$$\Gamma\left(r_R, r_E\right) = \sqrt{\frac{\Delta r^2\left(r_R, r_E\right)}{\delta r^2} + \frac{\Delta D^2\left(r_R, r_E\right)}{\delta D^2}},$$

$\gamma\left(r_R\right) = \min\left\{\Gamma\left(r_R, r_E\right)\right\}\forall\left\{r_E\right\}$ where δr and δD are acceptance criteria for DTA and ΔD, respectively.

Table 1. Beam profile measurements for photon and electron beams.

Beam profile measurements		Equipment	Field size cm^2	Depth
PDDs	Photon	Semiflex, 0.125 cc chamber (PTW)	4 × 4, 8 × 8, 10 × 10, 15 × 15, 35 × 35	From the depth of 30 cm to the phantom surface
	Electron		10 and 20 applicators	From the depth of 10 cm to the phantom surface
In-plane and cross-plane	Photon		4 × 4, 8 × 8, 10 × 10, 15 × 15, 35 × 35	10 cm
	Electron		10 and 20 applicators	R_{100}

Table 2. Point measurements for photon and electron beams.

	Point measurements	Equipment	Field size cm^2	SSD (cm)
Photon measurements	Output factor ($S_{c,p}$)	Farmer ion chamber (0.6 cc) (PTW)	5 × 5, 8 × 8, 15 × 15, 25 × 25, 35 × 35	100
	Wedge factor		10 × 10	90
	TPR 20/10		10 × 10	80 and 90 on the surface of the phantom
Electron measurements	Output factor	Advanced Markus chamber (PTW)	5 × 5, 15 × 15, 20 × 20, 25 × 25	100

In the literature, for γ index amylases, both 2 mm/2%(7) and 3 mm/3%(6, 7, 9) acceptance criteria were used. In this study, for the PDD curves and beam profiles we calculated γ index and acceptance criteria of 3 mm/3% and 2 mm/2% as for $\delta r/\delta D$. Values of γ below 1 indicated that the comparison passed with respect to criteria. The acceptance threshold for point measurements according to Siemens ATP was ±1%(11). For γ calculations, an in-house code was written in MATLAB (The Mathworks Inc Ra2010) software. Also the penumbra (20–80% isodose line) for two accelerators was determined for 10 × 10 cm^2 field size in ATP and the results were compared.

Results

All measurements are summarized in Tables 3–5 and Figures 1–4. All depth dose curves were normalized to the dose of the maximum to generate PDDs. All in-plane and cross-plane curves were normalized to the central axis value.

Photon measurements

Output factor

For 6 MV photon beam, differences between the output factors of the two linacs were less than 0.5%. For 15 MV photon beam, the differences are within 1% with one exception of 1.5% for 35 × 35 cm^2 field size (Table 3).

Wedge factor

The wedge factors are in good agreement between two Linacs (Table 3). In 6 MV photon beam, the maximum relative difference between wedge factors was 1% which was for 15-degree wedge. For 15 MV photon beam, the maximum relative difference between wedge factors was 0.5% for 30-degree wedge.

TPR 20/10 (quality index)

The TPR 20/10 were measured for two Linacs and two available photon energies include 6 and 15 MV (values present in Table 3). Measurements were in 10 × 10 cm^2 field size and at the two depths of the 10 and 20 cm, which the ion chamber was at the isocenter. For 6 MV, the TPR 20/10s were 0.678 and 0.675 for Linac 1 and Linac 2, respectively, the difference was 0.44%. For 15 MV, the TPR 20/10 were 0.763 and 0.764 for Linac 1 and Linac 2, respectively, the difference was −0.1%. The penumbra for 6 and 15 MV for both LINACs were calculated and the results are presented in Table 3.

Photon PDD curves

A good agreement between two linacs was found in terms of PDDs for both 6 and 15 MV beams (Figure 1). All the PDD curves pass the 3 mm/3% and 2 mm/2% γ criteria after the buildup region, except two PDD curves at 6MV and 15MV for 4 × 4 cm^2 field size for 2 mm/2% criteria.

Photon beam profiles

15 out of 20 beam profiles present good agreement between two Linacs. For 15 MV, the 3 mm/3% criteria fail at 15 × 15 and 35 × 35 cm^2 field sizes. Also, the 2 mm/2% criteria fail at 10 × 10, 15 × 15 and 35 × 35 cm^2 field sizes. Details presented in Table 4 and Figure 2a–d.

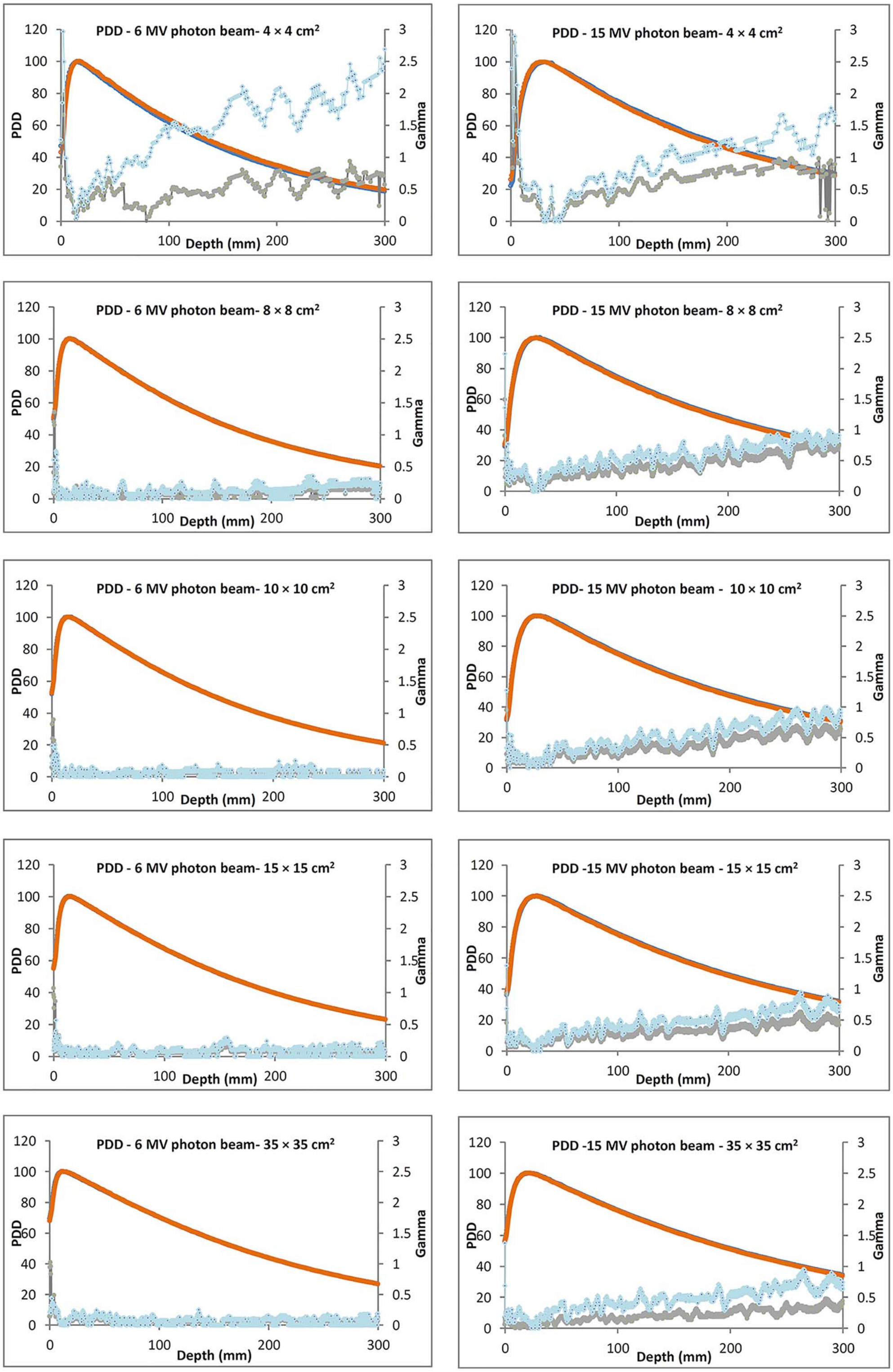

Figure 1. PDDs for 6 and 15 MV photon beams at different field sizes. The γ values are also present along with the PDD curves: blue lines indicate the 2 mm/2%, gray lines indicate 3 mm/3%.

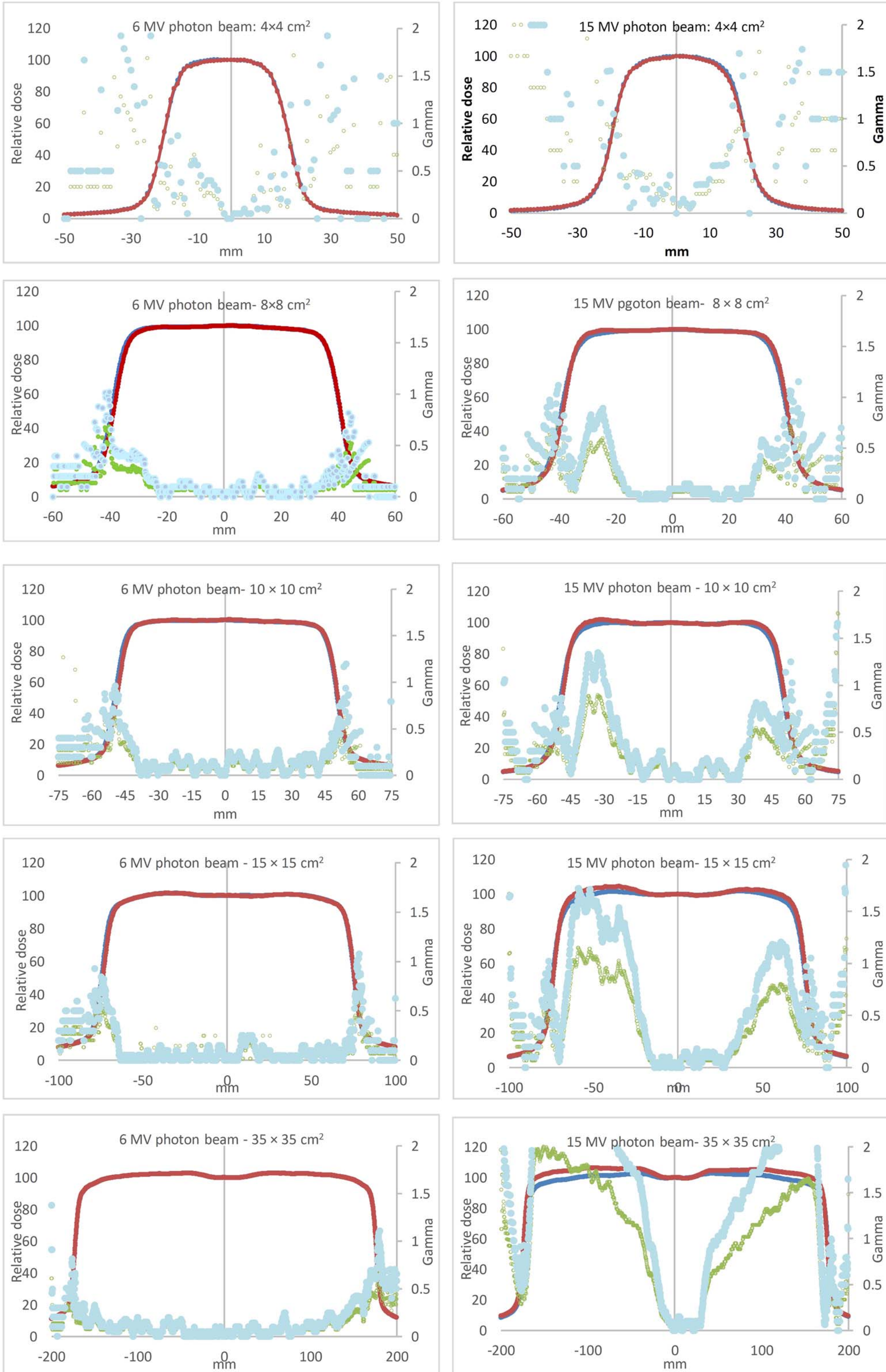

Figure 2. Beam profiles for 6 and 15 MV photon beams at different field sizes. The γ values are also present along with the beam profile curves: blue lines indicate the 2 mm/2%, green lines indicate 3 mm/3%.

Table 3. Percentage deviation of point measurements for photon beams.

Absolute values			6 MV			15 MV		
			Linac 1	Linac 2	Difference (%)	Linac 1	Linac 2	Difference (%)
TPR 20/10			0.678	0.675	0.3	0.763	0.764	−0.1
WF (15)			0.68	0.69	−0.1	0.745	0.75	0.2
WF (30)			0.52	0.53	−1.0	0.59	0.60	−0.5
WF (45)			0.32	0.32	−0.4	0.41	0.40	0.1
Output factor ($S_{c,p}$)	Field size (cm^2)	5 × 5	0.940	0.938	−0.2	0.929	0.937	0.8
		8 × 8	0.977	0.974	−0.3	0.981	0.979	−0.2
		15 × 15	1.032	1.027	−0.5	1.034	1.032	−0.2
		25 × 25	1.064	1.061	−0.3	1.069	1.063	−0.6
		35 × 35	1.076	1.075	−0.1	1.088	1.073	−1.5
Penumbra (mm)					Criteria Below 10 mm			Criteria Below 10 mm
		In-plane	6.76	6.61	Accept	7.61	7.75	Accept
		Cross-plane	6.54	6.30	Accept	7.96	7.71	Accept

Table 4. The γ values in photon beam profiles.

	3 mm/3% criteria				2 mm/2% criteria			
	6 MV		15 MV		6 MV		15 MV	
Field size (cm^2)	Maximum γ value in nominal field size[a]	Status	Maximum γ value in nominal field size	Status	Maximum γ value in nominal field size	Status	Maximum γ value in nominal field size	Status
4 × 4	0.76	Accept	0.67	Accept	0.87	Accept	0.71	Accept
8 × 8	0.30	Accept	0.60	Accept	0.45	Accept	0.89	Accept
10 × 10	0.19	Accept	0.90	Accept	0.29	Accept	1.35	Reject
15 × 15	0.32	Accept	1.14	Reject	0.25	Accept	1.72	Reject
35 × 35	0.17	Accept	1.98	Reject	0.25	Accept	2.96	Reject

[a]The separation between the 50% dose level points on the beam profile.

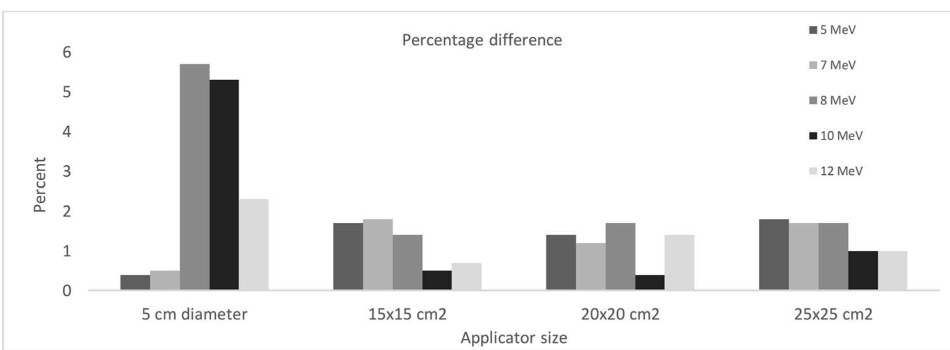

Figure 3. Percentage change of the output factor between two Linacs at five electron energies.

Electron measurements

Percentage difference in the output factors for electron beams are presented in Figure 3. The largest difference (5.7%) of output factor between two Linacs was for 8 MeV and applicator with 5 × 5 cm^2 diameter. Except for energies of 8, 10 and 12 MeV in the 5 × 5 cm^2 applicator, the percentage difference between of output factors between two Linacs on all applicator sizes were less than 2%.

Electron PDD curves

All the PDDs after build-up region present good agreement between two linacs ($\gamma < 1$) for 3 mm/3% criteria. Three out of six PDD curves had $\gamma \geq 1$ in build-up

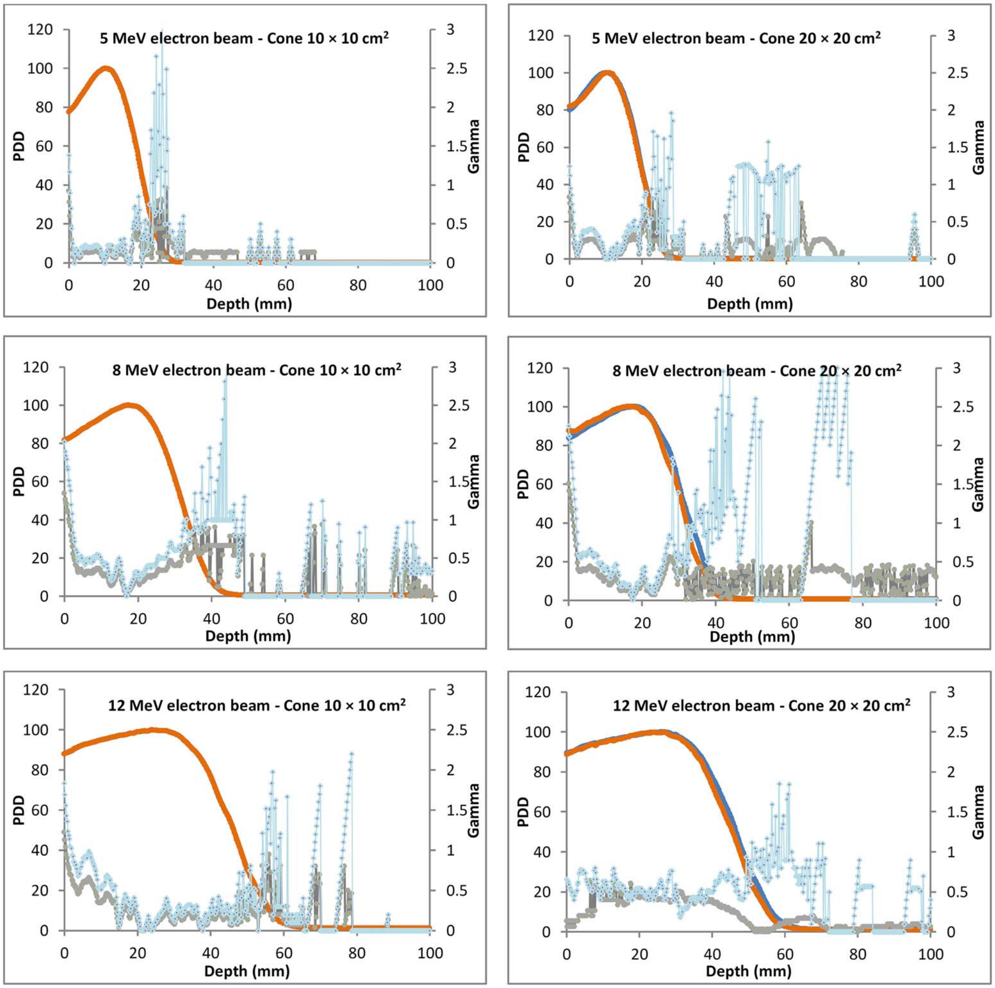

Figure 4. The PDD and related γ values for electron beams: blue lines indicate the 2 mm/2%, gray lines indicate 3 mm/3%.

Table 5. γ values for electron beam profiles.

	5 MeV			8 MeV			12 MeV		
Field size (cm^2)	Maximum γ value in nominal field size[a]		status	Maximum γ value in nominal field size		status	Maximum γ value in nominal field size		status
	3 mm/3%	2 mm/2%		3 mm/3%	2 mm/2%		3 mm/3%	2 mm/2%	
10 × 10	0.47	0.71	Accept	0.44	0.66	Accept	0.50	0.62	Accept
20 × 20	0.38	0.57	Accept	0.33	0.50	Accept	0.27	0.41	Accept

[a]The separation between the 50% dose level points on the beam profile.

region. These were seen in 8 MeV in both 10 × 10 and 20 × 20 cm^2 cone sizes and in 12 MeV in 10 × 10 cm^2 cone size. The maximum γ values for 8 MeV were 1.34 and 1.50 in 10 × 10 and 20 × 20 cm^2 cone sizes, respectively, located in build-up region. The maximum γ value for 12 MeV was 1.22 in 10 × 10 cm^2 cone sizes (Figure 4) located in build-up region. All the PDDs fail the acceptance γ criteria of 2 mm/2% ($\gamma > 1$).

Electron beam profile

The largest γ value in nominal field size for both 3 mm/3% and 2 mm/2% criteria ranging between 0.27

and 0.71, which were in acceptable range. Largest γ value was 3.50, which was in out-of-field region (low-dose region).

Discussion

Radiotherapy treatment of patients can be disrupted for a variety of reasons, including machine downtime or service time. The ideal procedure during unscheduled treatment interruptions is to transfer patients to a beam-matched Linac[5]. Two Siemens Primus Linacs with 6 and 15 MV photon beams and 5, 7, 8, 10 and 12 MeV electron beams were installed in our hospital with time interval of 1 y. Although two accelerators fulfilled the Siemens ATPs, the level of beam-matching between two Linacs have not been assessed. The goal of this study was the evaluation of two similar Linacs produced by the same vendor. Our analysis was based on γ index analysis of beam profiles and PDDs and evaluation of absolute values. The γ index combines dose difference and distance-to-agreement to evaluation of 1D (e.g. PDDs and/or beam profiles), 2D (e.g. film measurement) or 3D (e.g. gel dosimetry, Monte Carlo simulation) dose distributions([12,13]).

For point measurements the Siemens ATPs has determined the beam-matching limit to be ±1% in the photon and electron beam characteristics([11]), also we used 3 mm/3% and 2 mm/2% for γ acceptance criteria for beam profiles. Watts[14] compared a series of six Linacs with the same vendor during a 12-month. He performed acceptance testing for all six Linacs and compared dosimetric parameters for available photon and electron beams. He concluded that most beam parameters have variation less than 1%. Also, all the variations between beam parameters were less than 2%, which can be related to precision measurement. This is within acceptance level of clinical tolerance. Accordingly, we use 2% as clinically acceptance criteria for clinical use.

In total, 18 points were evaluated for photon beams. Of these, 17 points had a difference of less than 1%. One point had a difference of 1.5%, which is clinically acceptable. All 6 and 15 MV photon PDDs had a γ less than 1 after the build-up region for both 2 mm/% and 3 mm/3% acceptance criteria (except for 4 × 4 cm^2). The 6 MV photon beam profiles had a γ less than 1 in all field sizes. The 15 MV photon beam profiles in field sizes smaller than 10 × 10 and 15 × 15 cm^2 pass the acceptance criteria of γ 2 mm/2% and 3 mm/3%, respectively.

A total of 20 points were evaluated for electron beams. Of these, 3 points had a difference of more than 2% and 17 points had a difference of less than 2%. All the PDDs and electron beam profiles were in complete agreement for γ acceptance criteria of 3 mm/3%. The electron beams are not beam-matched in case of γ acceptance criteria of 2 mm/2%.

Conclusion

According to the measurements, it can be said that 6 MV photon beam in all field sizes (except 4 × 4 cm^2) are beam-matched. This is not true in case of 15 MV photon beams. The electron beams in all applicator sizes (except 5 × 5 cm^2 applicator) pass the acceptance γ criteria of 3 mm/3% ($\gamma < 1$). Electron beams are not beam-matched in the case of the acceptance γ criteria of 2 mm/2%. This work focus on the physical parameters of two Linacs. Further investigations should be done in terms of TPS calculation and dose delivery phase.

Data availability statement

Using the data and figures are available to public with permission.

Funding

This work was supported by the Advocate Center for Clinical Research, Ayatollah Yasrebi Hospital.

References

1. Baskar, R., Lee, K. A., Yeo, R. and Yeoh, K.-W. *Cancer and radiation therapy: current advances and future directions*. Int. J. Med. Sci. **9**(3), 193 (2012).
2. Delaney, G., Jacob, S., Featherstone, C. and Barton, M. *The role of radiotherapy in cancer treatment: estimating optimal utilization from a review of evidence-based clinical guidelines*. Cancer **104**(6), 1129–1137 (2005).
3. Lu, L. *Dose calculation algorithms in external beam photon radiation therapy*. Int. J. Caner Ther. Oncol. **1**(2), 4 (2013).
4. Miften, M. *et al. Tolerance limits and methodologies for IMRT measurement-based verification QA: recommendations of AAPM task group no. 218*. Med. Phys. **45**(4), e53–e83 (2018).
5. Donaldson, S. L. Timely Delivery of Radical Radiotherapy: Guidelines for Management of Unscheduled Treatment Interruptions. (London: The Royal College of Radiologists, Society and College of Radiographers, Institute of Physics and Engineering in Medicine, National Patient Safety) (2008).
6. Attalla, E. M., Abou-Elenein, H., Ammar, H. and Eldesoky, I. *Dosimetric evaluation of a beam matching procedure*. Chinese-German J. Clin. Oncol. **13**(2), 89–93 (2014).
7. Sjöström, D., Bjelkengren, U., Ottosson, W. and Behrens, C. F. *A beam-matching concept for medical linear accelerators*. Acta Oncol. **48**(2), 192–200 (2009).
8. Sarkar, B. *et al. A mathematical approach to beam matching*. Br. J. Radiol. **86**(1031), 20130238 (2013).
9. Low, D. A., Harms, W. B., Mutic, S. and Purdy, J. A. *A technique for the quantitative evaluation of dose distributions*. Med. Phys. **25**(5), 656–661 (1998).

10. Hussein, M., Clark, C. and Nisbet, A. *Challenges in calculation of the gamma index in radiotherapy–towards good practice*. Phys. Med. **36**, 1–11 (2017).
11. Bhangle, J. R., Narayanan, V. S., Kumar, N. K. and Vaitheeswaran, R. *Dosimetric analysis of beam-matching procedure of two similar linear accelerators*. J. Med. Phys. **36**(3), 176 (2011).
12. Hrbacek, J., Depuydt, T., Nulens, A., Swinnen, A. and Van den Heuvel, F. *Quantitative evaluation of a beam-matching procedure using one-dimensional gamma analysis*. Med. Phys. **34**(7), 2917–2927 (2007).
13. Hussien, M. Evaluation of Detector Array Technology for the Verification of Advanced Intensity-Modulated Radiotherapy. (United Kingdom: University of Surrey) (2015).
14. Watts, R. J. *Comparative measurements on a series of accelerators by the same vendor*. Med. Phys. **26**(12), 2581–2585 (1999).