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Evaluation of two beam-matched linear accelerators for volumetric modulated arc therapy

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ABSTRACT

Background: Currently, Mahavajiralongkorn Thanyaburi Hospital has two linear accelerators (LINACs) of identical models and brands with volumetric modulated arc therapy (VMAT) capability. Since two identical LINAC systems have been installed for two years, it is of great interest to determine beam-matching techniques in order to interchange ongoing irradiated patients between the two LINACs without re-planning if any malfunction of one machine occurs.

Objectives: This study aimed to verify the dosimetric accuracy of beam-matching using VMAT plans after completing the extended beam-matching.

Materials and methods: After completing the acceptance test and initial vendor-recommended beam-matching test, the extent of beam-matching was measured to evaluate the level of beam matching in both LINACs. The original LINAC (LINAC 1) photon beams were selected as the reference for beam tuning of the second LINAC (LINAC 2). Planar dose measurements of head and neck, thorax, and pelvis regions were collected from 30 retrospective cancer patients. The VMAT plans were generated in the Monaco Treatment Planning System (TPS) using a 6 MV photon beam model. TPS doses calculated by LINAC 1 were used as a reference for all measurements. The LINAC 1's verification plans were irradiated in both LINACs by doing the machine override option available in LINAC 2 consoles. All of the VMAT plans were measured using the Octavius^{4D} dosimetry system. The data of Octavius measurement were compared with the TPS calculated planar doses with gamma criteria of 3% dose difference, and 3 mm distance to agreement (3%/3mm). In addition, the statistically significant differences for gamma passing rates of Octavius measurements between two LINACs was analyzed using a paired sample t-test at a 95% confidence interval (CI).

Results: For all thirty cases, the gamma passing rates of Octavius measurements on two beam-matched LINACs were higher than 95% with 3%/3mm gamma criteria. The mean gamma passing rates of LINAC 1 and LINAC 2 were 96.2±0.8% and 96.3±0.8%, respectively. There was no statistical difference in the gamma passing rates between LINAC 1 and LINAC 2 (*p*-value = 0.094).

Conclusion: The beam-matched LINACs showed good agreement between measurements and TPS calculations for VMAT plans. Insignificant differences in gamma passing rates between two LINACs prove the viability of interchanging VMAT patients between two beam-matched LINACs without re-planning VMAT plans to manage the machine downtime.

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Introduction

Beam matching has been increasingly used in centers with two or more radiotherapy treatment machines from a similar manufacturer. Beam matching is helpful for interchanging the patients between machines in case of machine failure without re-planning, preserving patient's time to continue their treatment, and reducing staff workload. Most of the previous studies reported dosimetric data for evaluating the feasibility of machine matching such as depth dose, beam profile, and output factors[1–11]. In addition, some studies extended the validation of beam matching to clinical patient treatment plans.[5,7] However, few studies performed patient-specific quality assurance by measuring the actual dose using point dose and planar dose.[8–10]

Recently, two identical models and brands of linear accelerators (LINACs) systems with volumetric modulated arc therapy (VMAT) treatment capability were installed at Mahavajiralongkorn Thanyaburi Hospital. The first was installed in 2016, and the second was consecutively installed in 2018. As two identical LINACs are available in our center, it is a great opportunity to try using beam matching techniques. The final purpose of this study was to interchange ongoing irradiated patients between the two LINACs without re-planning when any malfunction of one machine might occur. In our institution, machine breakdown occurs approximately 6 times a year. Therefore, interchanging patient purposes is beneficial.

To best our knowledge, few studies performed the actual measurement. However, there was no study utilized the Octavius[4D] dosimetric system for evaluating the dose of the treatment machine. Therefore, this study aimed to verify the dosimetric accuracy of beam matching using the Octavius[4D] dosimetric system for VMAT plans in head and neck, chest and pelvis regions.

Materials and methods

Two identical linear accelerators of Elekta Infinity (Elekta AB, Stockholm, Sweden) with an agility head (80 MLC leaf pairs of 5 mm leaf width) were evaluated for beam matching in this study. Both linear accelerators are equipped with XVI cone-beam computed tomography (CBCT) and iView GTTM portal imaging. The desktop software is Integrity 3.2. Each LINAC has two-photon beams of nominal energies 6 and 10 MV and five electron beams with nominal energies of 6, 9, 12, 15, and 18 MeV. Figures 1a and 1b illustrate the linear accelerators used in this study.

Figure 1. *1a: Original LINAC (LINAC 1), 1b: The second LINAC (LINAC 2).*

A preliminary study of beam matching was performed in our previous study.[12] We reported the comparison dosimetric parameters according to the initial vendor-recommended beam-matching of the two LINACs available in our center. The summary of dosimetric parameters of 6 MV photon beam for LINAC 1 and LINAC 2, including depth dose, beam profile at 10 cm depth, and output factor, are illustrated in Table 1-3. In addition, the beam quality in terms of tissue phantom ratio at depth 20 cm and 10 cm ($TPR_{20,10}$) of LINAC 1 and 2 were 0.679 and 0.677, respectively. The difference of $TPR_{20,10}$ between two LINACs was -0.29%. In Table 2, a high value of flatness was found mainly in large field sizes. However, the criteria of the Elektra machine were 106% for field sizes between 10x10 cm^2 and 30x30 cm^2 and 110% for field sizes greater than 30x 30 cm^2 according to the IEC protocol recommended in the customer acceptance test. The acceptable criterion of this difference for flatness and symmetry between beam-matched LINACs should be within ±2%.[13]

Table 1 Comparison of depth dose parameters between 2 linear accelerators.

Parameters	LINAC 1	LINAC 2	Difference
R_{100} (FS 5x5 cm^2) (cm)	1.50	1.60	0.10
R_{100} (FS 10x10 cm^2) (cm)	1.50	1.60	0.10
R_{100} (FS 20x20 cm^2) (cm)	1.40	1.43	0.03
R_{100} (FS 30x30 cm^2) (cm)	1.30	1.39	0.09

R_{100} is a range of 100% depth dose

Table 2 Comparison of flatness and symmetry of beam profiles between 2 linear accelerators.

Field size (cm^2)	In-plane				Cross-plane			
	Flatness (%)		Symmetry (%)		Flatness (%)		Symmetry (%)	
	LINAC 1	LINAC 2	LINAC 1	LINAC 2	LINAC 1	LINAC 2	LINAC 1	LINAC 2
5x5	101.37	101.58	101.03	100.24	101.78	101.99	100.24	100.53
10x10	103.00	103.99	100.62	100.70	104.52	104.67	100.63	100.88
15x15	104.07	104.93	101.02	100.76	104.60	105.26	100.44	100.62
20x20	103.05	105.02	100.87	100.83	103.42	104.43	100.42	100.92
30x30	103.02	104.28	101.07	101.03	103.24	104.74	100.70	101.09

Flatness = (D_{max}/D_{min}) x 100, Symmetry = $[max(D_{left}, D_{right})/min(D_{left}, D_{right})]$ x 100

Table 3 Comparison of output factors between 2 linear accelerators.

Field size (cm^2)	LINAC 1	LINAC 2	% difference
2x2	0.810	0.809	-0.12
3x3	0.848	0.847	-0.12
4x4	0.879	0.877	-0.23
5x5	0.906	0.905	-0.11
10x10	1.000	1.000	0.00
15x15	1.058	1.060	0.19
20x20	1.097	1.098	0.09
30x30	1.143	1.146	0.26
40x40	1.161	1.167	0.52

Dose measurement for clinical VMAT cases

The clinical assessment of beam matching between LINAC 1 and 2 was conducted in thirty cancer patients by collecting regions of head and neck, thorax, and pelvis, with ten patients for each region in this retrospective study. VMAT treatment plans were created in the Monaco (version 5.11.02) Treatment Planning System (TPS) (Elekta Oncology Systems, Crawley, UK) using 6 MV photon beam models of LINAC 1 for all patients. The doses were calculated using the Monte Carlo algorithm with a calculation grid size of 0.3 cm with the prescribed dose and other parameters described in Table 4. Treatment doses calculated on LINAC 1 were taken as a reference for all measurements.

Table 4 Treatment planning parameters for cancer patients used in this study.

Parameters	Head and Neck		Thorax		Pelvis
	GBM	NPC	Lung cancer	Esophagus cancer	Prostate cancer
Photon energy (MV)	6	6	6	6	6
Prescribed dose (cGy)	5940	7000	6000	5040	7800
Number of fractions	33	33	30	28	39
Number of arcs	2	2	2	1	2
Number of patients	3	7	4	6	10

The planar dose measurements were conducted using the Octavius^{4D} dosimeter (PTW, Freiburg, Germany). It is a cylindrical unit of 32 cm diameter and 34 cm length. To keep the consistency of measurement, the measured plane of the detector array aligns with the center plane of the cylinder which can be rotated in synchrony with the LINACs gantry using input from the inclinometer. All measurements were performed using the Octavius detector 1500 with 1405 plane-parallel vented ionization chambers uniformly arranged in a 27x27 cm^2 area. Each ionization chamber has a dimension of 4.4 mm x 4.4 mm x 3 mm (0.06 cm^3). The VeriSoft® software (version 6.2) was used for the measurement and dose analysis.

LINAC 1's verification plans were applied to set the irradiation in LINAC 1 and LINAC 2 rooms using the machine override option available in LINAC 2 consoles. Then VMAT treatment plans were evaluated using Octavius^{4D} phantom with VeriSoft® verification software. Figure 2 illustrates the measurement set-up geometry for this study. The doses of Octavius measurement were compared with the TPS calculated planar doses using gamma comparison with criteria of 3% dose difference and 3 mm distance to agreement (3%/3mm). The gamma passing rate between LINAC 1 and LINAC 2 was compared as a percentage of difference, and a statistically

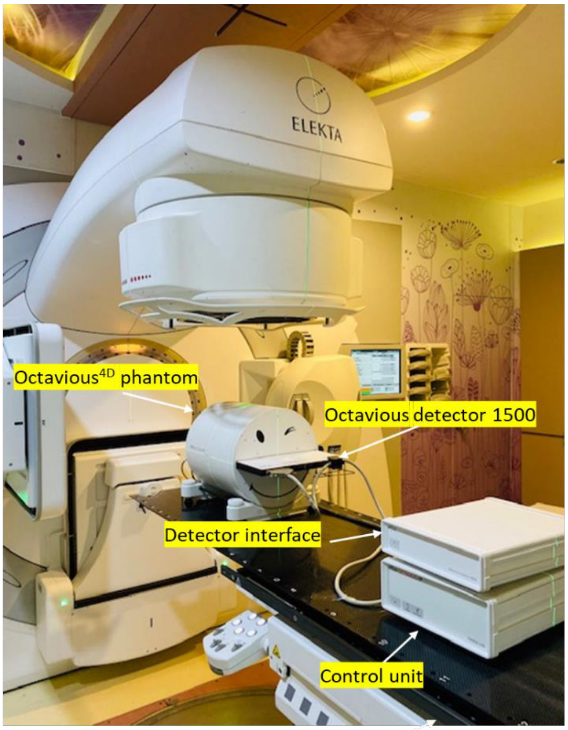

Figure 2. *Geometry of measurement.*

significant difference for gamma passing rates of Octavius measurements between LINAC 1 and LINAC 2 was analyzed using paired sample t-test at a 95% confidence interval (CI).

Results

Depth dose, beam profile, and output factors between LINAC 1 and LINAC 2 were comparable, as depicted in Table 1-3. More dosimetric parameters of photon and electron were reported in our previous study.[12] In this study, we extended the evaluation for clinical data of patients undergoing VMAT plans. In Figure 3, the gamma passing rates of Octavius measurements on two beam-matched LINACs were higher than 95% with 3%/3mm gamma criteria in all patients.

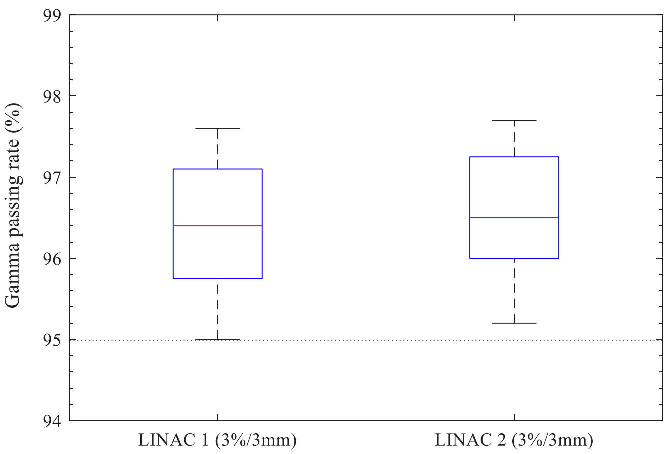

Figure 3. *Distributions of the average gamma passing rate of VMAT plans delivered on two beam matched LINACs.*

Percentage differences of gamma passing rate between LINAC 1 and LINAC 2 for thirty cases are demonstrated in Figure 4. The differences were within 1.1%. However, most of the gamma passing rates obtained from LINAC 2 were higher than those values obtained from LINAC 1, as illustrated by the positive percentage difference.

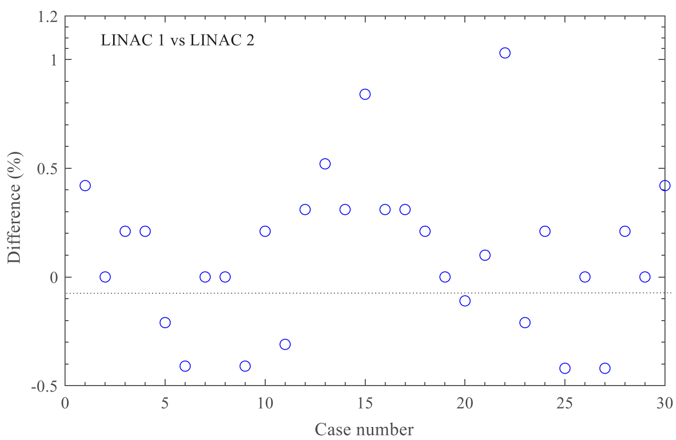

Figure 4. *Distributions of the percentage difference of gamma passing rate between 2 LINACS for thirty cases.*

Average gamma passing rates of LINAC 1 and LINAC 2 were 96.2±0.8% and 96.3±0.8%, respectively, as shown in Table 5. In addition, there was no statistically significant difference in the gamma passing rates between LINAC 1 and LINAC 2 (*p*-value = 0.094).

Table 5 Comparison of mean gamma passing rate and standard deviation (SD), and paired sample t-test analysis between LINAC 1 and LINAC 2.

Regions	Mean gamma passing rate (%) ± SD	
	LINAC 1	LINAC 2
Head and Neck (n=10)	96.6±0.9	96.6±0.9
Thorax (n=10)	96.0±0.8	96.2 ±0.8
Pelvis (n=10)	96.0±0.7	96.1±0.9
Total (n=30)	96.2±0.8	96.3±0.8
t-test (*p* value)	0.094	

Discussion

After beam matching, LINAC 1 and LINAC 2 in our center have similar beam energies for photon and electron beams.[12] For advanced techniques, the clinical implementation of beam matching should be more intensively considered for reducing the dosimetric error in patient dose delivery. The dosimetric analysis of the VMAT plan of head and neck, thorax, and pelvis swapped between two machines are well within clinical acceptable. In addition, the evaluation of beam matching with patient-specific quality assurance using Octavious dosimeter was a good agreement for all cases. Therefore, interchanging VMAT patients between two beam-matched LINACs without re-planning VMAT plans to manage the machine downtime could be acceptable. The mean gamma passing rate for each region was comparable between LINAC 1 and LINAC 2. The highest difference was found in case number 22 for the pelvic region, with a percentage difference of 1%, as shown in Figure 4.

In Table 5, mean gamma passing rate of LINAC 2 was slightly higher than LINAC 1. One of the reasons for these results might be affected by the time of beam tuning. Since the LINAC 2 was the newer machine tuned using the dosimetric data from LINAC 1, the commissioning data was transferred to a treatment planning system and used to model the VMAT plans in this study. Therefore, the newer machine might be closed to the treatment planning data, resulting in good agreement between TPS and measurement. However, the difference data might be due to the daily output variation of the machines. The clinical results in this study confirmed the finding from previous publications that beam-matched LINACS are undoubtedly possible.[8–10] However, regular quality assurance should be performed for evaluating the matched beam LINACS.

In this study, a quantitative evaluation of beam matching of two LINACs in terms of identical model and brand was performed for the Elekta machines. This methodology has advantages over our preliminary study of beam matching using dosimetric parameters such as depth doses, beam profiles, and output factors.[12] To improve the clinical workflow and maintain high patient throughputs when interchange patients among beam-matched LINACs, the dosimetric accuracy of VMAT plans was evaluated based on 3%/3mm criteria according to the protocol used in our center. However, the difference in gamma passing rate criteria was not taken into account for the dosimetric accuracy evaluation. This was a limitation of this study. According to the update report published by AAPM TG-218, using γ3%/2mm is recommended for the appropriate criteria.[14] Therefore, the evaluation in other gamma passing rate criteria should be performed for further study.

Field sizes used in this study were limited from medium (5x5 cm^2) to large (30x30 cm^2) field sizes. Smaller field sizes (less than 5x5 cm^2) which are widely used in advanced techniques such as VMAT and stereotactic radiosurgery, were not included in the depth dose and beam profiles. In addition, output factors were conducted in field sizes larger than 2x2 cm^2. Munoz L *et al*. recently performed the small field dosimetry in beam-matched LINACS.[3] They found that the beams were matched for large field size and still matched down to field size 1x1 cm^2. For regular quality assurance for beam-matched LINACS, the assessment in a small field size should be incorporated. Moreover, treatment plan parameters comparison such as Planning Target Volume (PTV), body, and organ at risk (OAR) doses should be incorporated in order to confirm the clinical significance of beam matching in both LINACs.

Conclusion

Beam-matched LINACs show good agreement between measurements and TPS calculations for VMAT plans. In addition, slight differences in gamma passing rates between two LINACs prove the viability of interchanging VMAT patients between two beam-matched LINACs without re-planning VMAT plans to manage the machine downtime. However, these measurements should be frequently measured/re-checked and compared between LINAC systems in a part of hospital quality assurance programs, especially when interchange occurs.

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