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AN INTERCOMPARISON OF MULTIPLE BEAM MATCHED LINEAR ACCELERATORS COMMISSIONED ACCORDING TO THE ACCELERATED GO LIVE PROGRAM

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Abstract. *Beam matched accelerators is a modern concept in radiation therapy field applied in the clinics where more than one linear accelerator is employed for treatment with important benefits for the medical team and patients alike. Our primary goal was to analyze and compare the dosimetric parameters of 8 linear accelerators with Elekta's ultra-efficient install and commissioning program - Accelerated Go Live (AGL). AGL significantly reduces data gathering requirements by providing high quality, reliable, reference beam data, including beam profiles and percent depth doses (PDD) for all photon and electron energies. The machine's parameters were matched to the reference parameters for each of the three photon energies. The measurements were acquired with Semiflex 3D ionization chambers in the BeamScan water phantom and processed with Mephysto software. After all the measurements were completed, we compared them with AGL reference data. The agreement was the following: Photon beams quality varied 95% agreement within 1% and 1mm for PDD, and within 2% and 2mm for beam profiles. Output factors agreed within 0.2% on average. Commissioning data have beam measured and analyzed with the gamma criteria required by vendor and present a good agreement. This study is similar to an internal audit and highlights the beam matching between involved linacs.*

Keywords: *beam matched linacs, radiation therapy, photon beams, dose profiles, PDD, out-put factors, gamma analysis, commissioning*

1. INTRODUCTION

Elekta (Crawley, UK) offers the possibility to its users to choose the predefined beam models for photons and electrons beams reducing the commissioning process to a few days, against the traditional commissioning process where beam data is collected for all energies and multiple field sizes. In the case of conventional beam data collection, the medical physicists team measure a high amount of data including dose profiles, percentage depth dose (PDD) and out-put factors (OFs) for all beams delivered by the machine; data that is sent to producer (Elekta) to develop a personalized beam model for each energy and algorithm of calculation. This process takes around 3 weeks. On the other hand, in the case of predefined beam models, the Accelerated Go Live (AGL) process is employed. AGL process includes the machine installation and calibration to match the reference dose profiles and PDDs and requires only 5 days of beam model validation before going live (clinical start). AGL significantly reduces data gathering requirements by providing high quality, reliable, reference beam data, including beam profiles and percent depth doses (PDD) for all photon and electron energies.

Our primary goal was to analyze and compare the dosimetric parameters of 8 linear accelerators with Elekta's ultra-efficient install and commissioning program - Accelerated Go Live (AGL) with the aim to highlight beam-matching between linacs. Beam matching advantages are: possibility to interchange patients without replanning, possibility to perform treatment planning quality assurance (QA) on any of the machines and development of machine quality assurance procedures identical for all centers.

2. MATERIALS AND METHODS

Elekta (Crawley, UK) linacs are able to deliver photon and electron beams for a variety of treatments techniques from conformal 3D radiotherapy (3D-CRT), to intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). 8 medical linear accelerators are involved in this study (7 Elekta Infinity and 1 Elekta Versa HD). All linacs are equipped with a multi-leaf collimator system (Elekta Agility MLC) designed from 160 tungsten leafs, 0.5cm width. Minimum field size aperture is $0.5x0.5cm^2$ and the maximum is $40x40cm^2$.

The machine's parameters were matched to the reference parameters for each of the three photon energies (6MV, 10MV and 6MV FFF). Three of linacs are able to deliver also flattening filter free beams used with focus on stereotactic treatments. In the current study, only 6MV and 10MV flattened beams are included. The measurements were acquired with PTW Semiflex 3D ionization chambers in the BeamScan water phantom from PTW (Freiburg, Germany) and processed with Mephysto beam data analyzing software. The ionization chambers used for the AGL process are in agreement with manufacturer's (Elekta) requirements and international protocols: Absorbed

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Dose Determination in External Beam Radiotherapy (TRS-398) from International Atomic Energy Agency (IAEA) and Protocol for clinical reference dosimetry of high-energy photon and electron beams (TG-51) from American Association of Physicists in Medicine (AAPM). PTW Semiflex 3D is a vented cylindrical ionization chamber with 0.07cm^3 nominal sensitive volume, being appropriate to measure both, small and large fields, from 2.5x2.5cm^2 to a maximum of 40x40cm^2. The reference point of the chamber is on the chamber axis 3.45mm from the tip. This detector can be mount both radial or axial in the effective point of measurement. The water phantom PTW BeamScan can scan at high velocity of 20mm/sec with a precision of 1mm measurement step.

For this study two field sizes, 10x10cm^2 and 30x30cm^2, were included. 10x10cm^2 is the reference field size according to TRS-398 and TG-51.

The measurements set-up, in agreement with calibration set-up of the linac, is 90cm source-to-surface distance (SSD) and 10cm depth. At SSD 90cm and 10cm depth in water, 100 Monitor Units (MUs) delivered by the linac measures 100cGy.

2.1. Percentage depth dose

Percentage depth dose curve refers to absorbed dose distribution in the medium and characterizes the dose distribution on central axis. PDD curve varies with the dimension of the irradiated field, beam energy and source to surface distance (SSD) and it's calculated with the formula:

$$P = \frac{D_d}{D_{d0}} x100\% \quad (1)$$

where, D_d is the absorbed dose at any depth d, and D_{do} is the absorbed dose at a reference depth d_o. PDD curve is defined by two regions: the build-up region between the surface and the point of maximum dose dependent, and the slope. For PDD measurements, PTW Semiflex 3D ionization chambers were used for both, reference detector and field detector. Detector movement is set to be from bottom to top with 1mm step. Three parameters are analyzed: depth of maximum (R100), depth where the beam deposits 80% of the dose (R80) and percentage of dose deposition at 10cm depth (D100).

2.2. Dose profiles

Beam dose profiles are measured for cross-plane (X axis) and in-plane (Y axis) at three depths: 5cm, 10cm and 20cm. 10cm depth measurements are included in this study, as long as 10cm concur with the calibration depth of the linac. During the AGL process five field sizes are measured: 3x3cm^2, 5x5cm^2, 10x10cm^2, 30x30cm^2 and 30x40cm^2 (for wedge). Field size is defined by MLCs in cross-plane and by jaws in in-plane. The detector step chosen for this measurement is 2mm for the central region of the field, 1mm for the penumbra region and 2mm for umbra (out of field region). Profiles analysis involves central axis deviation (CAX), flatness, symmetry, penumbra and field size. All measured data was analyzed using Mephysto mc^2 software with Elekta predefined protocol. Central axis deviation represents the position of the field at the defined value with respect to the coordinate origin (between 50% values). The dosimetric field size is defined by the distance intercepted by 50% isodose on a plane perpendicular to the beam axis. Symmetry parameter is calculated regarding international code IEC 60976 as a dose ratio between two dose points from the profile situated at the same distance from the central axis. Penumbra is analyzed for both sides, left and right, and is defined as the distance between two dose points (20% and 80%) normalized to the central axis.

2.3. IMRT/VMAT Commissioning Tests

Beam matching between linacs goes beyond dosimetric parameters analysis and involves also IMRT and VMAT plan verification. The practical base line commissioning for IMRT and VMAT quality assurance procedure is established by AAPM Task Group 119. Dose distributions measurements were performed with PTW Octavius 1500 detector array using Octavius 4D modular rotation unit. The Octavius 1500 detector is a new concept of an ion chamber matrix for plan verification. In total, there are 1405 vented ion chambers displayed on 27x27cm^2 field size, uniformly, with 7.1mm detector spacing. For IMRT/VMAT commissioning, Elekta provides a set of seven treatment plans (2 IMRT, 5 VMAT) in accordance with TG-119 for different anatomical sites: head, head and neck and pelvis. All plans are imported in the treatment planning system (TPS) and calculated without optimization. After that, the plans are delivered, measured and analyzed for each linac involved in the study using 3D Gamma Analysis with 3% dose difference (DD) and 3mm distance-to-agreement (DTA) criteria, according to TG-119. A global analysis is performed and a minimum passing rate of 95% (95% of the analyzed points must pass the gamma criteria) is considered clinically acceptable.

3. Results

For this study PDDs for 10x10cm^2 field size (reference filed size) were analyzed. Reference value (AGL reference data) for depth of maximum for 6MV photon beam is 14.8mm and for 10MV photon beam is 21.3mm (Figure 1). Maximum deviation is 0.3mm for 6MV beams and 0.8mm for 10MV beams, in agreement with the maximum deviation allowed of 1mm from baseline.

The R80 (Table 1) parameter deviation for 6MV energy is neglectable (mean deviation of 0.22mm) and for 10MV mean deviation is 0.77mm.

The percentage of dose deposition at 10cm depth (D100) increases with energy (Table 2), for 6MV the value of D100 is around 65.9% for Elekta machines, and for 10MV is around 71%, as reported by AGL Data Book Reference Data for Versa HD – AGL machine. The 8 linacs involved in this study reported similar results for R80 parameter, with a maximum deviation of 0.5mm for 6MV photon beams and 1.47mm for 10MV. For higher energies, such is 10MV in this case, R80 parameters may vary due to neutron contamination. Neutrons are produced at those energies from photonuclear reactions due to photons interactions with the materials with high atomic number from the treatment head. The neutron contribution is small at this depth, as Homkhaow et al. (2021) showed in their study where they found the maximum to be at 3cm depth.

Table 1. Depth where the beam deposits 80% of the energy (R80) for 6MV and 10MV photon beams

ENERGY	REFERENCE	LINAC 1	LINAC 2	LINAC 3	LINAC 4	LINAC 5	LINAC 6	LINAC 7	LINAC 8
6MV	63.77	63.86	63.3	63.67	64.15	63.75	63.46	64	63.89
Deviation (mm)		-0.09	0.47	0.1	-0.38	0.02	0.31	-0.23	-0.12
10MV	75.96	74.49	76.49	75.43	75.12	74.62	75.65	75.55	75.23
Deviation (mm)		1.47	-0.53	0.53	0.84	1.34	0.31	0.41	0.73

Table 2. Percentage of dose deposition at 10cm depth (D100) for 6MV and 10MV photon beams

ENERGY	REFERENCE	LINAC 1	LINAC 2	LINAC 3	LINAC 4	LINAC 5	LINAC 6	LINAC 7	LINAC 8
6MV	65.89	65.86	65.63	66.03	66.03	65.85	65.67	65.95	65.88
Deviation (%)		0.03	0.26	-0.14	-0.14	0.04	0.22	-0.06	0.01
10MV	71.43	70.79	71.54	71.18	70.96	70.93	71.1	71.2	71.12
Deviation (%)		0.64	-0.11	0.25	0.47	0.5	0.33	0.23	0.31

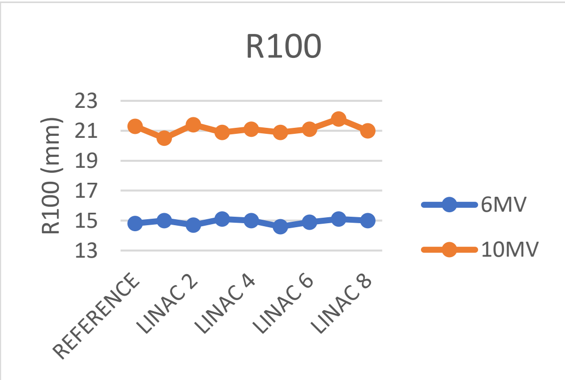

Figure 1. Depth of maximum (R100) for 6MV and 10MV photon beams

Table 3. Central axis deviation of the beams for 10x10cm² field size

Device	Energy				Mean value
	6MV		10MV		
	Cross plane	In plane	Cross plane	In plane	
REFERENCE	0.00	0.00	0.00	0.00	0.00
LINAC 1	-0.17	0.18	-0.09	0.28	0.05
LINAC 2	0.24	-0.17	0.14	-0.04	0.04
LINAC 3	0.22	0.43	0.04	0.26	0.24
LINAC 4	0.34	0.23	0.37	-0.06	0.22
LINAC 5	-0.08	0.22	0.14	0.23	0.13
LINAC 6	0.31	0.17	0.08	0.07	0.16
LINAC 7	0.22	0.02	-0.11	-0.18	-0.01
LINAC 8	0.07	0.16	0.01	-0.11	0.03

Gamma analysis in case of PDDs brings more accurate information in terms of beam matching than a simple analysis of dosimetric parameters such are: D100, R80 and R100. Therefore, all PDDs undergo 1D gamma analysis using 1% dose difference and 1mm distance-to-agreement criteria with good results. 100% of the measured data passed the 1%/1mm criteria with no additional adjustments needed.

Dose profiles were analyzed in terms of dosimetric parameters such are flatness, symmetry, penumbra, field size and central axis deviation of the beam and also with 1D gamma analysis. Gamma analysis was performed using Mephysto mc² software with 2% dose difference and 2mm distance-to-agreement criteria, as manufacturer asks. Each dose profile was compared with the reference data from AGL. 100% of dose profiles passed the gamma analysis with no additional adjustments. Therefore, from this point of view, we can conclude that all 8 linacs are beam-matched.

Table 4. Central axis deviation of the beams for 30x30cm² field size

Device	Energy				Mean value
	6MV		10MV		
	Cross plane	In plane	Cross plane	In plane	
REFERENCE	0.00	0.00	0.00	0.00	0.00
LINAC 1	-0.39	0.37	-0.23	0.29	0.01
LINAC 2	0.15	0.44	0.01	-0.23	0.09
LINAC 3	0.37	-0.06	0.26	0.60	0.29
LINAC 4	0.06	0.25	-0.19	-0.18	-0.02
LINAC 5	0.06	0.08	-0.29	0.25	0.03
LINAC 6	-0.01	-0.08	0.32	0.17	0.10
LINAC 7	-0.24	0.10	0.29	0.09	0.06
LINAC 8	0.02	-0.09	0.00	0.17	0.03

For dosimetric measurements it is important to center the detector precisely with respect to the central axis of the beam (CAX), otherwise the volume effect can average the accumulated ionization in the detector which will end up in a lower measured dose. This effect is more pronounced in case of small fields where detectors with a small sensitive volume are used (example PTW PinPoint). Central axis deviation of the beams can by directly influenced by human error, for example an inadequate positioning of the detector. PTW BeamScan software is able to check detector positioning and is used before each positioning of the chamber.

CAX deviation (mm) is reported in Table 3 and Table 4 for both field sizes. Small average deviation can be seen for both energies. This parameter gave us information that can be corelated with dose profiles shifts in one axis and can be changed by repositioning.

Table 5. Dosimetric field size

Energy	Field size (cm²)	Axis	REF.	LINAC 1	LINAC 2	LINAC 3	LINAC 4	LINAC 5	LINAC 6	LINAC 7	LINAC 8
6MV	10x10	Cross plane	10.148	10.105	10.094	10.077	10.084	10.044	10.080	10.099	10.091
		In Plane	10.118	10.062	10.071	10.044	10.043	10.021	10.066	10.036	10.027
	30x30	Cross plane	30.348	30.206	30.170	30.186	30.143	30.175	30.191	30.053	30.160
		In Plane	30.229	30.132	30.083	30.134	30.097	30.220	30.076	30.118	30.097
10MV	10x10	Cross plane	10.169	10.110	10.091	10.091	10.091	10.061	10.070	10.116	10.101
		In Plane	10.117	10.077	10.083	10.058	10.062	10.036	10.072	10.051	10.042
	30x30	Cross plane	30.358	30.208	30.231	30.186	30.271	30.172	30.171	30.206	30.193
		In Plane	30.245	30.150	30.161	30.098	30.210	30.125	30.203	30.087	30.099

Table 6. Average (left and right) penumbra (mm)

Energy	Field size (cm²)	Axis	REF.	LINAC 1	LINAC 2	LINAC 3	LINAC 4	LINAC 5	LINAC 6	LINAC 7	LINAC 8
6MV	10x10	Cross plane	8.01	8.29	8.50	7.85	8.09	7.86	7.67	7.88	7.86
		In Plane	6.53	6.60	6.61	6.41	6.47	6.50	6.55	6.43	6.45
	30x30	Cross plane	10.06	10.56	10.16	10.32	9.88	9.76	10.28	10.24	10.10
		In Plane	8.58	8.84	8.63	8.66	8.46	8.54	8.71	8.68	8.71
10MV	10x10	Cross plane	7.82	8.21	8.79	7.68	8.44	8.43	8.21	8.05	8.07
		In Plane	8.54	8.55	8.53	8.41	8.43	8.56	8.49	8.44	8.42
	30x30	Cross plane	9.33	9.72	10.22	9.22	9.83	9.91	9.46	9.57	9.58
		In Plane	8.33	8.52	8.46	8.27	8.34	8.56	8.22	8.38	8.36

The measured field size for all 8 linacs (Table 5) do not exceeded the uncertainty allowed by the manufacturer of 1% from the reference data provided by AGL data-set, found in table 5 as reference data. The maximum deviation for 6MV photon beam is 0.097cm for 10x10cm² and for 30x30cm² field size, maximum deviation is 0.295cm. In the case of 10MV photon beam, for 10x10cm² maximum deviation is 0.108cm and for 30x30cm² field size, maximum deviation is 0.187cm.

Penumbra main role is in the planning system where it brings an important benefit for the dose gradient at the field edges. The purpose of the treatment planning is to achieve a high dose gradient at the edge of the planning target volume (PTV) to reduce dose at organs at risk (OAR). Penumbra values are higher in cross-plane due to jaws removal. New generation of linear accelerators are designed with only one pair of jaws in Y axis with the aim to increase the speed of the MLCs. Due to this feature, cross-plane penumbra is slightly increase for both field sizes (Table 6). For 6MV energy beams, mean value of cross-plane penumbra for both 10x10cm² and 30x30cm² field size is increased with 1.5mm. In the case of 10Mv energy beams, the cross-plane penumbra for both field sizes is increased with 1.3mm.

Flatness and symmetry maximum deviation from baseline requested by the vendor is ±2%. All 8 linacs shows good agreement with the reference data, presented in Figure 2 (flatness) and Figure 3 (symmetry). For 10x10cm² field size, the baseline for flatness is 104.5% for 6MV cross-plane and 103.8% for 6MV in-plane profiles. For 30x30cm² field size, the baseline for flatness is 103.2% for 6MV cross-plane and in-plane profiles. Maximum deviation for cross-plane and in-plane analyzed data was less than 1% for both included field size. 10MV beams showed lower flatness values than 6MV, for 10x10cm² field size, the base line is 104.6% for cross-plane and 103.9% for in-plane. For 30x30cm² field size, reference flatness is 102.2% for cross-plane and 102.7% for in-plane. Maximum deviation is 0.7% for all analyzed data (see linac 2 and linac 6 10x10cm² cross-plane).

Symmetry base-line given by AGL data-set is 100% for each energy and field size. Maximum deviation from base-line is 1.1% for 10MV photon beam on a large field (30x30cm²).

Gamma analysis was performed in agreement with TG-119 criteria (3%DD/3mmDTA) with clinical acceptable results. Minimum passing rate for IMRT plans was 98.1% for 6MV energy (Table 7) and 98.65% for 10MV (Table 8). VMAT plans shows a minimum passing rate of 97.9% for both 6MV and 10MV.

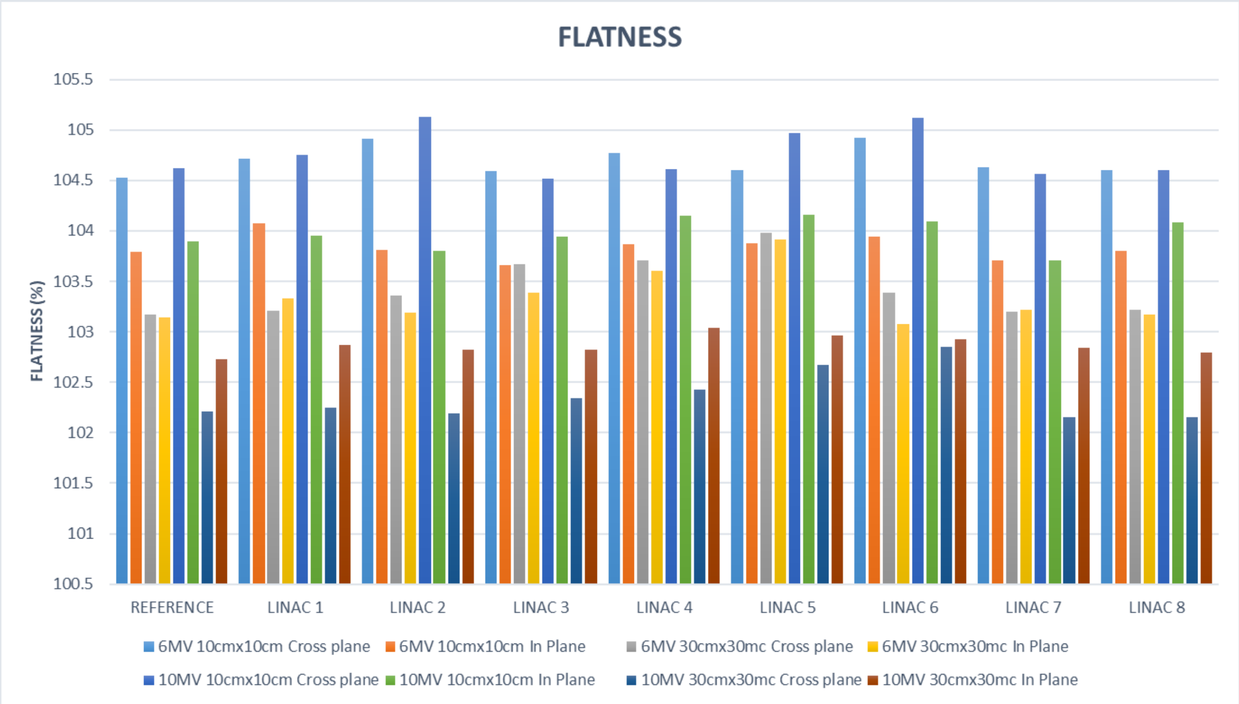

Figure 2. Flatness variation for 8 beam-matched linear accelerators 6MV and 10MV energies for 10x10cm^2 and 30x30cm^2

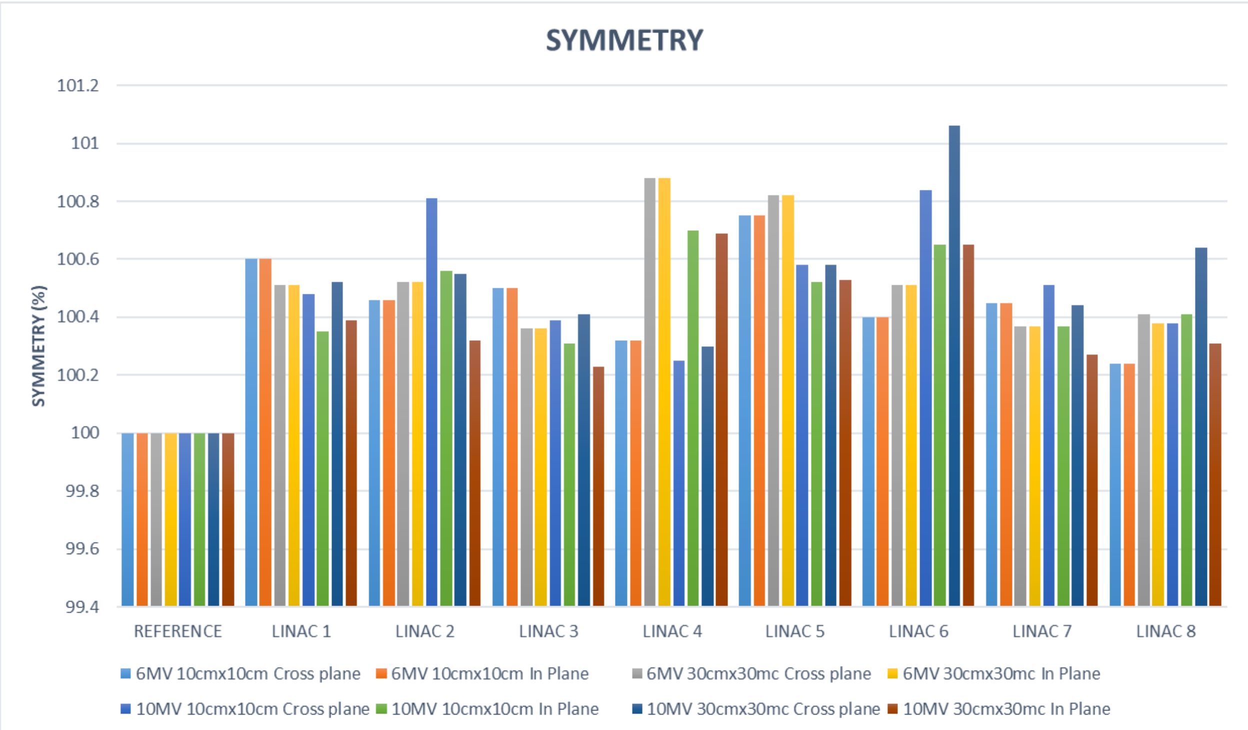

Figure 3. Symmetry variation for 8 beam-matched linear accelerators 6MV and 10MV energies for 10x10cm^2 and 30x30cm^2

Table 7. Gamma analysis results for IMRT/VMAT commissioning using 3%/3mm criteria for 6MV energy photon beams

Device	IMRT		VMAT				
	c119	headneck119	anal244	c119	headneck119	headneck244	prostate119
LINAC 1	99.6	99.2	99.8	99.7	99.8	99.9	99.9
LINAC 2	99.6	99.5	99.8	97.7	99.3	99.7	99.9
LINAC 3	99.0	98.6	99.0	97.8	99.0	99.3	99.8
LINAC 4	98.3	95.4	98.9	96.9	98.5	99.3	99.7
LINAC 5	99.2	98.5	98.8	98.5	99.1	99.1	99.9
LINAC 6	98.3	97.9	98.6	98.4	98.7	99	99.7
LINAC 7	99.2	97.8	99.2	97.6	99.3	99.8	99.9
LINAC 8	99.6	98.5	99.6	96.7	99.6	99.3	99.8
Mean ± SD	99.1±0.5	98.2±1.2	99.2±0.4	97.9±0.9	99.2±0.4	99.4±0.3	99.8±0.1

Table 8. Gamma analysis results for IMRT/VMAT commissioning using 3%/3mm criteria for 10MV energy photon beams

Device	IMRT		VMAT				
	c119	headneck119	anal244	c119	headneck119	headneck244	prostate119
LINAC 1	99.4	99.0	99.4	99.1	99.5	99.3	99.9
LINAC 2	99.4	99.3	99.2	100.0	99.3	98.6	99.9
LINAC 3	99.4	98.9	98.8	98.6	99.1	98.4	99.9
LINAC 4	98.3	96.1	96.1	95.2	97.9	97.7	99.7
LINAC 5	99.6	98.3	98.2	98.1	98.8	97.9	99.9
LINAC 6	99.2	99.1	98.9	97.9	99.1	98.8	99.9
LINAC 7	95.7	99.7	98.3	97.7	98.2	98.3	99.6
LINAC 8	99.3	98.8	98.2	96.7	98.7	99.2	99.8
Mean ± SD	98.8±1.2	98.7±1.0	98.3±0.9	97.9±1.4	98.8±0.5	98.5±0.5	99.8±0.1

4. Conclusion

In this study, dosimetric parameters consistency was analyzed among 8 Elekta linacs with the aim to highlight beam matching. All 8 linacs involved show a strong agreement between analyzed parameters: flatness, symmetry, penumbra, field size. 1D gamma analysis was performed for PDDs and profiles using manufacturer criteria and presents clinical acceptable results with passing rates higher than 95%. This intercomparison will be helpful in the case of patients interchange without replanning and quality assurance for treatment planning that can be performed on any of the involved linacs without additional labor for the medical physicist team.

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