Dosimetric beam matching analysis of MV photons and electrons therapy

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► ***Original article***

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Received: January 2021
Final revised: February 2022
Accepted: February 2022

Int. J. Radiat. Res., July 2022; 20(3): 693-700

DOI: 10.52547/ijrr.20.3.25

Keywords: *Breast Beam-matching, Clinac-iX Medical Linear Accelerator, photon beam data, electron beam data, dosimetric leaf gap, MLC.*

ABSTRACT

Background: For various practical reasons in radiotherapy practice, it is very advantageous to have linear accelerators dosimetrically matched. The present work assesses the extent of beam matching by investigating the similarity of dosimetric data from three Clinac-iX accelerators in photons (6, 18 MV) and electrons (6, 9, 12, 16 and 20 MeV) mode. ***Materials and Methods***: The following study is based on detailed comparisons of measured and determined parameters such as percent depth doses (PDDs), cross-plane beam profiles, flatness, symmetry, penumbra and dosimetric leaf gap, MLCT interleaf transmission factor, quality index, Relative output factor, in addition of depth R50, therapeutic range R90 and particle range Rp of electron beam. ***Results***: The current measured data, for both photons and electrons, exhibited satisfactory degree of agreement among the three Clinac-iX. For 6 MV and 18 MV photons energies the maximum deviation of percentage depth does not exceed 0.4 %. For electron depth dose measurements (d_{max}, R_{50}, R_{90}, R_p) the results revealed a maximum deviation of 0.54 mm for all electron energies and applicators. As a direct clinical application, a left breast and prostate cancer cases were planned on the three Clinac-iX machines and compared for their dose volume histograms. ***Conclusion***: In clinical applications, the patient's treatment can be shifted from one Clinac-iX to another without reducing the treatment quality in the case of periodic preventive maintenance or interruption of the functioning of the Clinacs; the treatment can be preserved without having to replan.

[DOI: 10.52547/ijrr.20.3.25]

INTRODUCTION

As introduced above, our radiation therapy center in Sétif (Algeria) is equipped by three Varian linear accelerators (Varian Medical Systems, Inc., Palo Alto, CA, USA) denominated Clinac-iX1, Clinac-iX2 and Clinac-iX3. They were received after checking few mechanical, geometric and dosimetric parameters which are insufficient for dosimetric equivalence between accelerators and consequently did not guarantee quality assurance for patients. In fact, the protocol is usually applied to check the difference at some points on the ionization curves for depth dose or beam profiles [4]. Consequently, detailed dosimetric measurements are required and necessary after commissioning.

Method of measurements

The methodology is mainly based on the dosimetric comparison between the three accelerators using a large beam data bank measured in photon (6 MV, 18 MV) and electron (6 MeV, 9 MeV, 12 MeV, 16 MeV, 20 MeV) modes. The quantities measured are the PDD, cross-plane beam profiles, flatness, symmetry, penumbra and dosimetric leaf gap, MLCT interleaf transmission factor, quality index, Relative output factor, in addition of depth R50, therapeutic range R90 and particle range Rp of electron beam. The beam data measurements are completed in accordance with recommendation of AAA (Anisotropic Analytical Algorithm version 11.0.31) for photon beam and eMC (Electron Monte Carlo) for electron beam in order to commissioning the treatment planning system (TPS) [19]. Beam data measurements were achieved in agreement with international practice and guidelines such as AAPM Task Group TG-106 [20]. We used the water Scanning System (MP3, PTW Freiburg, Germany) for dosimetric measurements; it is equipped with two ionization chambers, namely the 0.125 cm^3 (Semiflex, PTW Freiburg, Germany) and the 0.3 cm^3 (Semiflex, PTW Freiburg, Germany); the obtained data were handled using a Navigation software (MEPHYSTO mc^2, PTW Germany).

Photon beam measurements

Commissioning of percent depth doses (PDD's), cross-plane beam profiles, and output factors were performed on three Clinac-iX (Varian Medical Systems, Palo Alto, CA) for the standard photon energies 6MV, 18MV. The measured depth ionization curves for five electron beams energies

(6MeV- 20MeV) were converted to dose curves using IAEA TRS-398 formalism executed in software MEPHYSTO mc². The depth of dose maximum and PDD at 10 cm was assessed for five field sizes: 2 × 2 cm^2, 6 × 6 cm^2, 10 × 10 cm^2, 20 × 20 cm^2, and 40 × 40 cm^2. Note that a special consideration is required in dose measurement for small field 2×2 cm^2 [21, 22]. We have used the recommended 3D ionization chamber with a small active volume of 0.016 cm^3 (Pinpoint 3D, PTW Freiburg, Germany) [23, 24]. For comparison purposes, we used the beam quality index $TPR_{20/10}$ as defined in TRS-398 [25]; it is determined from the measured PDD_{20cm} and PDD_{10cm} data using: $TPR_{20/10}$ = $1.2661PDD_{20/10}$ – 0.0595, where $PDD_{20/10}$ is the ratio of percent depth at 20 cm and 10 cm. The flatness and the symmetry in the beam profiles at 10 cm were compared for field sizes of 2×2 cm^2, 10 ×10 cm^2 and 30 ×30 cm^2. Flatness can be quantified as a maximum permitted percentage variation from the average dose across the central 80% of the full width at half maximum (FWHM) of the profile in a plane transverse to the beam axis [26]. The beam flatness F was assessed by finding, first the maximum d_{max} and d_{min} dose point values on the beam profile within the central 80% of the beam width and then calculating F = $(d_{max}–d_{min})$ / $(d_{max}+d_{min})$. Symmetry calculation of the beams was also considered and found to be satisfactory. Beam profile penumbra was evaluated by considering the 80% and 20% relative dose points; the field size was defined as the width at 50% relative dose. We performed statistical analysis for uniform field sizes using symmetric jaws. For non- uniform MLC setups, surface penumbra and uniformity index parameters are suggested instead of conventional definition of physical penumbra [27]. Note that alternatively to the use of the water scanning system MP3, the 2D- Array-729 can be used for the routine quality control of photon beam profiles within the limit ±3% [28].

Leaf gap measurements

For photon beams, the MLC should be considered in the commissioning. Our linear accelerators have smoothed rounded shaped MLC leaves; they modify the radiation field by the transmission over the end portion of the leaves [29]. As a consequence, it is important to evaluate and include the dosimetric leaf gap (DLG) in the treatment planning system; it compensates for transmission and has important impact in IMRT and Rapid-Arc planning where high dose rate is used. DLG's were measured along the source axis distance setup at 10 cm depth. Following the vendor's procedure, executables of programmed sliding MLC field gaps denoted g with constant speed of 2mm, 4mm, 6mm, 10mm, 14 mm, 16 mm and 20 mm have been used. Control points are attributed to the position of the leaves every 10 mm. More details are given in reference [30]. Leaf gap measurement is performed for 6 MV and 18 MV. DLG is defined by plotting the gap size g function of the corrected gap reading R_g:

$$g(R_g) = a \times R_g + b \quad (1)$$

$$R_g = (r_g - R_{gT}) \quad (2)$$

$$r_{gT} = R_T(1-g(mm)) / 120mm \quad (3)$$

$$R_T = (R_{t,A} + R_{t,B}) / 2 \quad (4)$$

The value at the point of intersection (equation 1) along the x-axis is the DLG value. The corrected gap reading R_g (equation 2) is calculated from each gap g with r_g the meter reading with gap size g; r_{gT} (equation 3) is the contribution of average MLCT leaf transmission. R_T (equation 4) is the average MLCT transmission for bank A and B.

Total scatter collimator factors and head scatter measurements

Total scatter collimator factors (TSCF) and head scatter (HSc) were measured for 6 MV and 18 MV photon beams with open square fields 3×3 cm^2, 5×5 cm^2, 7×7 cm^2, 10×10 cm^2, 15×15 cm^2, 20×20 cm^2, 30×30 cm^2 and 40×40 cm^2. The reference field size is taken as 10×10 cm^2. HSc measurements were performed with an ionization chamber (0.125 cm^3 sensitive volume) housed at 10 cm depth in a mini-phantom (ESTRO mini-phantom, PTW Freiburg, Germany) made of acrylic and shaped as a cylinder (4 cm diameter, 17 cm long).

Electron beam measurements

For the case of electrons, PDDs measurements from the three linear accelerators Varian Clinac-iX are performed for 6 MeV, 9 MeV, 12 MeV, 16 MeV and 20 MeV with an ionization chamber of 0.125 cm^3. Electron applicators of 6x6 cm^2, 10×10 cm^2, 15×15 cm^2, 20×20 cm^2 and 25×25 cm^2 field sizes are considered in the present study; they collimate the beam, limit the radiation field and offer consistency of the dose at irradiated zone. MeV electron beams have limited range; a 15 cm depth is sufficient to measure the PDDs for the five energies cited before. In practice, the energy of the electron beam is usually quantified by its distal depth corresponding to 90 % of maximal dose, it represents the dose used to cover the planned target volume; the structure immediately adjacent is critical [31].

Statistical analysis

For our analysis to the variation of the different measurements, we focused on the mean and the standard deviation; the 95% confidence interval (CI) was calculated using Student's t-distribution (Addinsoft XLStat 2020). The Mann-Whitney Monte Carlo statistical analyses was used to evaluate p-values (Addinsoft XLStat 2020). $P<0.05$ was

[DOI: 10.52547/ijrr.20.3.25]

considered statistically significant.

RESULTS

Photon and electron measurements have been performed on the three Clinac-iX (1, 2, 3). Percentage depth doses (PDDs) for 6 MV and 18 MV photons are presented table 1 and table 2 with their detailed analysis for field sizes 2×2 cm^2, 6×6 cm^2, 10×10 cm^2, 20×20 cm^2 and 40×40 cm^2. For both photon energies, differences in maximum dose d_{max} were all within 0.2 mm; Differences in PDDs varied from 0.1% to 0.4% for 6MV photons and from 0.1% to 0.2% for a 18MV beam when comparing the PDD's at depths 5 cm (PDD5%), 10 cm (PDD10%) and 20 cm (PDD20%) with their corresponding mean values. On the same tables, $TPR_{20/10}$ data (Ratio of the tissue phantom at 20 and 10 cm) shows no differences reflecting the beam quality; Figure 1 displays our measurements of TSCF and HSc for 6 MV and 18 MV, respectively; Differences in the TSCF and HSc ranged from 0.001 to 0.005 for both energies and field sizes 3×3 cm^2, 5×5 cm^2, 7×7 cm^2,10×10 cm^2, 15×15 cm^2, 20×20 cm^2, 30×30 cm^2 and 40×40 cm^2. MLCT factor for the bank A and bank B were measured separately. For field size 10 x10 cm^2 and energies 6MV and 18 MV, the maximum differences in the MLCT were within 0.02%; the average resulting DLG from the three Clinac-iX, calculated with the help of equations (1 - 4), is found to be 1.53 mm for 6 MV and 1.63 mm for 18 MV with maximum difference of 0.05 mm (0.05 mm SD).

Extensive measurements of relative dose profile (cross-plane) for both 6 and 18 MV beams normalized to 100% at the central axis at 10 cm depth for different field sizes are performed on the three Clinac-iX. Their corresponding profiles are compared including their average relative dose profile as reference. A detailed analysis is presented on table 3 for 2×2 cm^2, 10×10 cm^2 and 30×30 cm^2 field sizes; We note that for 6 MV beam at 10 cm depth the maximum deviations in cross plane beam flatness and symmetry are within 0.6% and 0.58%, respectively; when excluding the small field 2×2cm^2, the maximum deviations in cross plane beam flatness and symmetry are within 0.2% and 0.58 %. Similarly, the maximum differences for 18MV beam are within 0.17 % and 0.38 %, respectively. In the penumbra region, the maximum values are 0.15 mm (Std.dev 0.18 mm) for 6 MV and 0.09 mm (Std.dev 0.08 mm) for 18 MV; For field size of 30×30 cm^2 these differences represent up to 25 % difference from the average value for 6 MV and up to 30% for 18 MV. Note that this region area is clinically not significant. Statistical analyses using Mann-Whitney Monte Carlo method on commonly used beam profile of 30×30 cm^2 versus the average beam profile curve of the three Clinac-iX result to p-values (5% significance level) of p=0.731 (Clinac-iX1), p=0.572 (Clinac-iX2), p=0.967 (Clinac-iX3) for 6 MV and p=0.314 (Clinac-iX1), p=0.282 (Clinac-iX2), p=0.334 (Clinac-iX3) for 18 MV. These findings confirm that the three machines are not different; which justifies the consideration that all three Clinac-iX are dosimetrically matched in regard to the beam profile. Additionally, for more explorations, we have measured diagonal profiles of 40×40 cm^2 field size from the three linear accelerators including their corresponding average curve for 6 MV and 18MV; Their statistical analyses with Mann-Whitney Monte Carlo non parametric tests have been found very satisfactory; thus, concluding the dosimetric equivalence of the three Clinac-iX along the diagonal profile.

In electron mode, a complete set of PDD measurements have been performed on the three Clinac-iX for 6 MeV, 9 MeV, 12 MeV, 16 MeV and 20 MeV electron beams with electron applicators of 6×6 cm^2, 10×10 cm^2, 15×15 cm^2, 20×20 cm^2 and 25×25 cm^2. As an example, figure 2 shows our PDD measurements (6 MeV, 9 MeV, 12 MeV, 16 MeV and 20 MeV electron beams) for the smallest applicator 6x6 cm^2 and the largest one of 25×25 cm^2; A detailed data analysis of these PDD measurements for the five energies (10x10 cm^2 applicator) is presented on table 4. Comparisons of PDD statistical analysis data for the five electron beam energies and five applicators cited above among the three Clinac-iX were found to be very reassuring; we found a maximum deviation of 0.53 mm (0.46 std.dev) at a depth of maximum dose (d_{max} or R100), a max.dev of 0.52 mm (0.45 SD) for R50 (the range of 50% from the range at d_{max}), a max. dev of 0.51 mm (0.45 SD) for R90 and 0.54 mm (std. dev 0.48) for the practical range Rp.

Note that other measurements necessary for the configuration of the treatment planning system in electron mode have also been carried out; the most important ones are measurements of the source surface distance (SSD) data and the open profile in air data. Their statistical analysis showed a good agreement within the three Clinac-iX.

From the whole data presented in the present study in photon and electron mode performed on the three Clinac-iX in our center, the statistical analysis presented in tables 1-4 is in general very realistic and encouraging; in particular, the 95% confidence intervals for the standard values look very conclusive; thus, offer control for the projected reproducibility. In fact, as evaluated during the commissioning, our results and analysis show that there is no significant variation among the three machines.

As a direct clinical application of our dosimetric beam matching analysis, we planned two cases on the three Clinac-iX; a left breast cancer case where we used a 3D conformal radiotherapy including the mono-isocentric and field in field techniques; the

[DOI: 10.52547/ijrr.20.3.25]

second is a hypo fractionated protocol for prostate cancer (60 Gy/ 20 fractions/ 3 Gy per fraction) planned with intensity modulated radiotherapy using the dynamic multi-leaf collimator (IMRT-sliding windows technique). The resulting histogram dose-volume (HDV) of the planning target volume (PTV 50 Gy), left lung and mean dose of heart are presented on figure 3 for the left breast case; The HDV of the prostate cancer case are shown on figure 3, they include the PTV 60 Gy, the rectum, the Bladder and Right femoral head. Clearly for both cases, the HDVs from the three machines are close to a single line; which again confirm that there is no significant clinical variation among the three machines.

Table1. Commissioning data parameters for 6MV photon beams and variation among three Clinac-iX (MLCT is in %, DLG in mm).

Data	FS (cm^2)	Clinac-iX1	Clinac-iX2	Clinac-iX3	Average	Max.dev	Std.dev	95% CI
d_{max} (cm)	2×2	1.45	1.35	1.35	1.38	0.07	0.06	[1.24 - 1.53]
	6×6	1.40	1.40	1.40	1.40	0.00	0.00	[1.40- 1.40]
	10×10	1.40	1.50	1.40	1.43	0.07	0.06	[1.29- 1.57]
	20×20	1.40	1.40	1.30	1.37	0.07	0.06	[1.22- 1.51]
	40×40	1.20	1.30	1.30	1.23	0.07	0.06	[1.09- 1.38]
PDD5 (%)	2×2	81.1	81.2	81.2	81.2	0.10	0.06	[81.0- 81.3]
	6×6	84.7	84.7	84.6	84.7	0.10	0.06	[84.5- 84.8]
	10×10	86.0	85.8	85.8	86.1	0.30	0.31	[85.3- 86.8]
	20×20	87.2	87.5	87.0	87.2	0.30	0.25	[86.6- 87.9]
	40×40	87.9	88.2	87.8	88.0	0.20	0.21	[87.4- 88.5]
PDD10 (%)	2×2	58.2	58.5	58.8	58.5	0.30	0.30	[57.8- 59.2]
	6×6	63.5	63.6	63.6	63.6	0.10	0.06	[63.4- 63.7]
	10×10	66.3	66.2	66.2	66.3	0.10	0.15	[66.0- 66.7]
	20×20	69.5	69.6	69.2	69.4	0.20	0.21	[68.9- 70.0]
	40×40	71.4	71.8	71.4	71.5	0.30	0.23	[71.0- 72.1]
PDD20 (%)	2×2	30.5	30.9	31.3	30.9	0.40	0.40	[29.9- 31.9]
	6×6	35.1	35.2	35.1	35.1	0.10	0.06	[35.0- 35.3]
	10×10	38.0	38.0	38.0	38.0	0.00	0.00	[38.0- 38.0]
	20×20	42.2	42.4	41.9	42.2	0.30	0.25	[41.5- 42.8]
	40×40	45.3	45.7	45.3	45.4	0.30	0.23	[44.9- 46.0]
MLCT	10×10	1.50	1.49	1.47	1.49	0.02	0.02	[1.44- 1.53]
DLG	10×10	1.53	1.58	1.48	1.53	0.05	0.05	[1.40- 1.65]
$TPR_{20/10}$	2×2	0.604	0.610	0.615	0.610	0.006	0.010	[0.596-0.623]
	6×6	0.639	0.640	0.641	0.640	0.001	0.001	[0.638-0.642]
	10×10	0.666	0.667	0.667	0.667	0.001	0.001	[0.665-0.668]
	20×20	0.710	0.712	0.708	0.710	0.002	0.002	[0.705-0.715]
	40×40	0.743	0.746	0.744	0.744	0.002	0.002	[0.741-0.748]

Table 2. Commissioning data parameters for 18MV photon beams and among three Clinac-iX (MLCT (%), DLG (mm)).

Data	FS (cm^2)	Clinac-iX1	Clinac-iX2	Clinac-iX3	Average	Max.dev	Std.dev	95% CI
d_{max} (cm)	2x2	3.15	3.00	3.04	3.06	0.09	0.08	[2.87- 3.26]
	6x6	3.40	3.50	3.40	3.43	0.07	0.06	[3.29- 3.58]
	10x10	3.10	3.10	3.10	3.10	0.00	0.00	[3.10- 3.10]
	20x20	2.50	2.60	2.60	2.60	0.10	0.06	[2.42- 2.71]
	40x40	2.30	2.20	2.30	2.27	0.07	0.06	[2.12- 2.41]
PDD5 (%)	2x2	95.1	94.9	95.0	94.9	0.20	0.10	[94.8- 95.2]
	6x6	97.2	97.1	97.2	97.2	0.10	0.06	[97.0- 97.3]
	10x10	96.1	96.1	95.9	96.0	0.10	0.12	[95.7- 96.3]
	20x20	93.8	93.9	94.0	93.9	0.10	0.20	[93.7- 94.1]
	40x40	93.0	92.9	93.2	93.0	0.20	0.15	[92.7- 93.4]
PDD10 (%)	2x2	75.9	75.6	75.8	75.7	0.20	0.21	[75.2- 76.3]
	6x6	79.4	79.4	79.4	79.4	0.00	0.00	[79.4- 79.4]
	10x10	79.2	79.2	78.9	79.1	0.20	0.17	[78.7- 79.5]
	20x20	78.0	78.1	78.1	78.1	0.10	0.06	[77.9- 78.2]
	40x40	78.1	77.9	78.2	78.1	0.20	0.15	[77.7- 78.4]
PDD20 (%)	2x2	48.3	48.2	48.4	48.3	0.10	0.15	[47.9- 48.6]
	6x6	51.6	51.7	51.6	51.6	0.10	0.06	[51.5- 51.8]
	10x10	52.5	52.6	52.4	52.5	0.10	0.10	[52.3- 52.7]
	20x20	53.2	53.3	53.3	53.3	0.10	0.06	[53.1- 53.4]
	40x40	54.4	54.2	54.4	54.3	0.10	0.12	[54.0- 54.6]
MLCT	10x10	1.55	1.55	1.52	1.54	0.02	0.02	[1.50- 1.58]
DLG	10x10	1.64	1.68	1.58	1.63	0.05	0.05	[1.51- 1.76]
$TPR_{20/10}$	2x2	0.746	0.747	0.748	0.747	0.001	0.001	[0.745-0.749]
	6x6	0.762	0.765	0.764	0.764	0.002	0.002	[0.760-0.767]
	10x10	0.779	0.781	0.782	0.781	0.002	0.002	[0.777-0.784]
	20x20	0.805	0.804	0.805	0.805	0.001	0.001	[0.803-0.806]
	40x40	0.822	0.822	0.821	0.822	0.001	0.001	[0.820-0.823]

[DOI: 10.52547/ijrr.20.3.25]

Table 3. Beam profile analysis for three Clinac-iX linear accelerators at 10 cm depth (Cross plane beam Flatness (%), Cross plane beam Symmetry (%) and Penumbra Left/Right average (mm)).

E(MV)	Data	FS (cm^2)	Clinac-iX1	Clinac-iX2	Clinac-iX3	Average	Max.dev	Std.dev	95% CI
6	Cross plane beam Flatness	2x2	7.03	7.95	7.08	7.35	0.60	0.52	[6.07-8.64]
		10x10	2.70	2.45	2.36	2.50	0.20	0.18	[2.07-2.94]
		30x30	1.96	2.16	1.95	2.02	0.14	0.12	[1.73-2.32]
	Cross plane beam Symmetry	2x2	0.64	1.17	0.39	0.73	0.44	0.40	[-0.26-1.72]
		10x10	1.34	0.60	0.35	0.76	0.58	0.51	[-0.52-2.04]
		30x30	0.48	1.10	0.36	0.65	0.45	0.40	[-0.34-1.63]
	Penumbra Left/ Right average	2x2	3.29	3.54	3.48	3.44	0.15	0.13	[3.11-3.76]
		10x10	6.93	7.07	7.11	7.04	0.11	0.09	[6.80-7.27]
		30x30	8.96	8.98	9.16	9.03	0.13	0.11	[8.76-9.31]
18	Cross plane beam Flatness	2x2	9.53	9.48	9.35	9.45	0.10	0.09	[9.22-9.68]
		10x10	2.42	2.30	2.10	2.27	0.17	0.16	[1.87-2.67]
		30x30	1.67	1.86	1.80	1.78	0.11	0.10	[1.54-2.02]
	Cross plane beam Symmetry	2x2	0.47	0.63	0.38	0.49	0.14	0.13	[0.18-0.81]
		10x10	0.83	0.69	0.31	0.61	0.30	0.27	[-0.06-1.28]
		30x30	0.74	1.41	0.95	1.03	0.38	0.34	[0.18-1.88]
	Penumbra Left/ Right average	2x2	4.48	4.52	4.64	4.55	0.09	0.08	[4.34-4.75]
		10x10	8.21	8.20	8.22	8.21	0.01	0.01	[8.19-8.23]
		30x30	9.21	9.15	9.15	9.17	0.04	0.03	[9.08-9.26]

Table 4. Commissioning data parameters for 6, 9, 12, 16 and 20 MeV electron beams for 10x10 cm^2 applicator among three Clinac-iX.

E (MeV)	Data (mm)	Clinac-iX1	Clinac-iX2	Clinac-iX3	Average	Max.dev	Std.dev	95% CI
6	d_{max}	12.79	12.41	12.98	12.73	0.32	0.29	[12.0-13.5]
	R50	23.20	23.13	23.12	23.15	0.05	0.04	[23.0-23.3]
	R90	17.29	17.24	17.24	17.26	0.03	0.03	[17.2-17.3]
	Rp	29.29	29.14	29.20	29.21	0.08	0.08	[29.0-29.4]
9	d_{max}	20.50	20.01	20.01	20.17	0.33	0.28	[19.5-20.9]
	R50	35.66	35.54	35.48	35.56	0.10	0.09	[35.3-35.8]
	R90	27.46	27.37	27.30	27.38	0.08	0.08	[27.2-27.6]
	Rp	43.81	43.62	43.59	43.67	0.14	0.12	[43.4-44.0]
12	d_{max}	28.01	28.50	28.0	28.17	0.33	0.29	[27.5-28.9]
	R50	49.79	49.60	49.56	49.65	0.14	0.12	[49.3-50.3]
	R90	38.76	38.65	38.55	38.65	0.11	0.11	[38.4-38.9]
	Rp	60.20	59.97	59.96	60.04	0.16	0.14	[59.7-60.4]
16	d_{max}	30.40	30.40	31.19	30.66	0.53	0.46	[29.5-31.8]
	R50	66.09	66.09	66.14	66.11	0.03	0.03	[66.0-66.2]
	R90	50.62	50.66	50.70	50.66	0.04	0.04	[50.6-50.8]
	Rp	79.56	79.64	80.26	79.82	0.44	0.38	[78.8-80.8]
20	d_{max}	19.98	19.98	20.00	19.99	0.01	0.01	[20.0-20.0]
	R50	83.27	82.95	83.05	83.09	0.18	0.16	[82.7- 83.5]
	R90	58.94	58.79	58.82	58.85	0.09	0.08	[58.7- 59.1]
	Rp	101.35	100.88	101.12	101.12	0.24	0.24	[100.5-101.7]

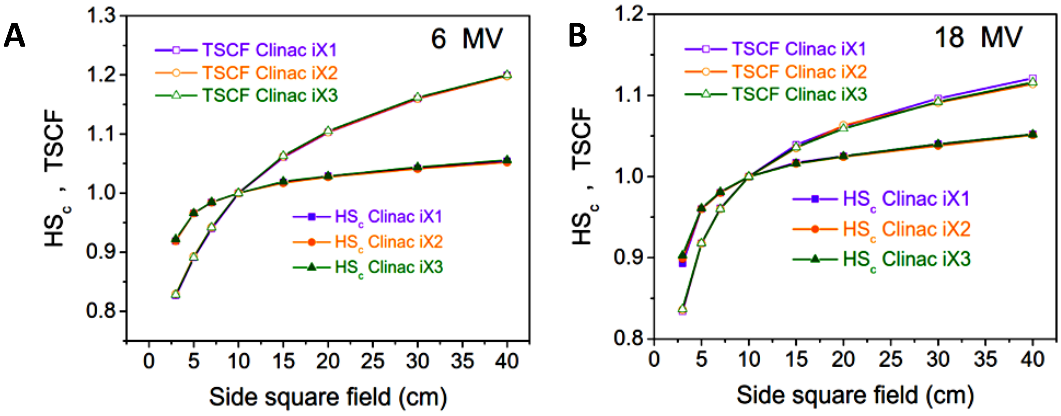

Figure 1. Measured Head Scatter Factor (HSc) in mini Phantom and Total Scatter factor (TSCF) in water versus Field size for three Varian Clinac-iX (**(A)** for 6 MV photon beam **(B)** for 18 MV photon beam).

[DOI: 10.52547/ijrr.20.3.25]

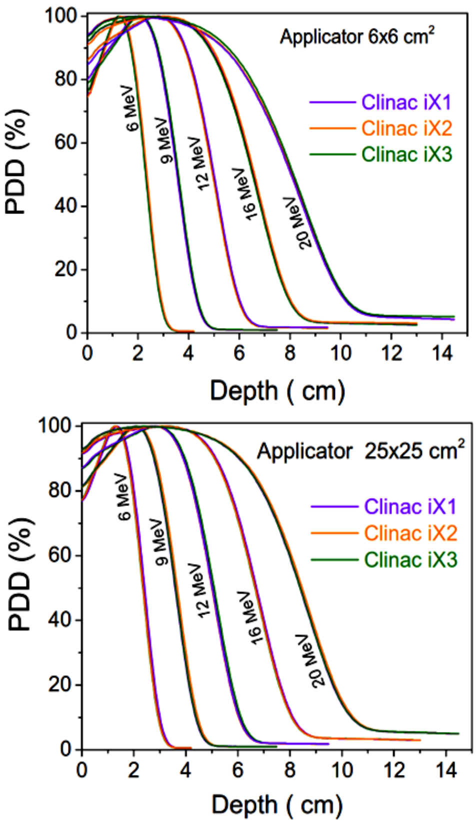

Figure 2. Measured PDD curves for the three Clinacs iX for all electron energies (**(A)** applicator size of 6x6 cm² **(B)** applicator size of 25x25 cm²).

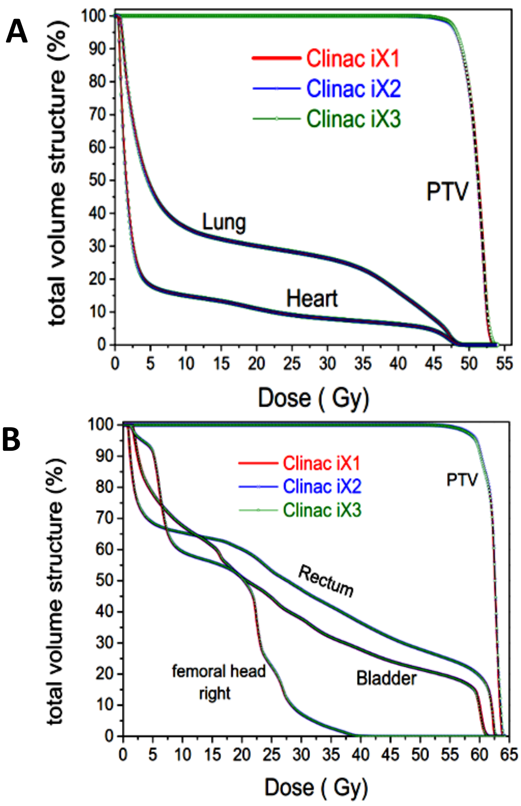

Figure 3. HDV of planning target volume and organs at risk for the three Clinacs iX (**(A)** left breast cancer case **(B)** prostate cancer case).

DISCUSSIONS

Our comparisons to similar studies showed in general very good agreement for most dosimetric quantities considered in our beam matching analysis; concerning the PDD where we have found differences not exceeding 0.3% for standard fields for both 6 and 18 MV are shown in tables 1 and 2, Kang *et al.* (2019) [6], Attalla *et al.* (2014) [5], Beyer (2013) [32], Bhangle *et al.* (2011) [4] and Sjöström *et al.* (2009) [3] PDD measurements were all matched within 1%. In contrast to Beyer (2013) [32] measurements of d_{max} maximum deviation of 2 mm, Krishnappan *et al.* (2018) [7] found a value of 1.2 mm; in our case, for d_{max}, the three machines are matched within 1 mm. Fenoglietto *et al.* (2016) [33] included small fields in their matching procedure to use for IMRT; they applied a threshold of 0.5 % in their PDD to match their linacs; As shown on tables 1, 2; for small field of 2×2 cm² we found a maximum deviation of 0.4% for both energies without imposing a threshold. The DLG and MLCT transmission are important parameters for IMRT; For 6 MV and 18 MV, our maximum deviation values of 0.05 mm and 0.02%, tables 1 and 2 and in our measurements among the three Clinac-iX are much better than those reported in Kang *et al.* (2019) [6] in their matching procedure for two VitalBeam linacs for 6 MV and 10 MV. Concerning the $TPR_{20/10}$, as reported on table (1 and 2) our measurements are better than those reported by Attalla *et al.* (2014) [5]. We found a standard deviation of 0.001 for field sizes of 10x10 cm² and 40x40 cm² in very good agreement with Beyer (2013) [32] measurements for 6 MV in their matching analysis for three true beam linacs; meanwhile for 18 MV, our results are much better for 10x10 cm². Sjöström *et al.* (2009) [3] found a $TPR_{20/10}$ maximum deviation of 0.004 and 0.003 for 6MV and 15 MV compared to our values of 0.001 and 0.002 for 6 MV and 18 MV, respectively. Variation of our measured TSCF for 6 MV and 18 MV did not differ more than 0.36% from the three Clinac-iX for all field sizes at 10 cm depth shown in figure 1 (A, B).

However, Kang *et al.* (2019) [6] measurements were within 1% for two VitalBeam linacs with 6 MV and 10 MV for all field sizes up to 30x30 cm²; Fenoglietto *et al.* (2016) [33] reported a value of 0.5% within two twin machines for 6, 8, 18 and 25 MV which is similar to Attalla *et al.* (2014) [5] measurements on two ONCOR machines for all field sizes for 6 and 10 MV. For the particular field size of 35×35 cm², Krishnappan *et al.* (2018) [7] found a 0.01 standard deviation from six non beam matched Varian linacs (6 MV); for our case we found a better much value of 0.001 standard deviation. For 6 MV, our TSCF and HS_c corresponding to 0.2% differences among the three Clinac-iX are better than Bhangle *et al.* (2011) [4] measurements of ±1% differences between two Siemens ONCOR machines for 4×4 cm² to 40×40 cm². In the detailed study of Kang *et al.*

(2019) [6], maximum differences in flatness and symmetry from five field sizes between two 6 MV VitalBeam linacs were 0.4% and -0.33%; In contrast, for field size of 10×10 cm^2 and 30×30 cm^2, we found maximum deviations of 0.2% and 0.58% respectively (table 3). For the penumbra width, our measurements are in agreement with those of Beyer (2013) [32]. In particular, the diagonal profile shown here in figure 2 (A, B) for 6 and 18 MV agree quit well with measurements of figure 7 of Beyer (2013) [32] on their Clinac 2100 and Trilogy machines. Concerning the PDD measurements in electron mode, the maximum deviation of d_{max}, R_{50}, R_{90}, R_p of the average is found to be 0.49 mm, 0.48 mm, 0.51 mm and 0.54 mm, respectively. Our findings are better than those of Hrbacek *et al.* (2007) [1]; they used two matched Varian clinacs 2100C/D for all energies and applicator and found a maximum deviation of ±1.5 mm of the average for d_{max} and ±1mm for R_{50}, R_{90}, R_{80}. A slightly higher value of 0.7 mm maximum deviation of average has been reports by Sjötröm *et al.* (2009) [3] for two parameters R_{50}, R_{85} using eight Varian iX machines for all energies and applicators. Similar maximum deviation value of 0.7 mm has been found by Attalla *et al*. (2014) [5] for R_p, R_{50}, R_{80}, R_{85}, R_{90} using two Siemens ONCOR. Clearly, our maximum deviation is very encouraging reflecting the fine beam matching among the three Clinac-iX for electron and photon modes used in our center.

Regarding the clinical application of our matching procedure where the resulting DVHs are close to a single line, similar finding has been shown in figure 2 by Kang *et al*. (2019) [6] for prostate cancer using two VitalBeam linacs. Note that the same dosimetric matching procedure in photon mode we use was adopted by Kang *et al*. (2019) [6]; In the same manner in a recent consistent clinical study, Krishnappan *et al*. (2018) [7] used six non-beam matched Varian linacs to confirm that overall results from DVHs remain within the limit of clinical acceptability; in fact, using 3DCRT, IMRT and Rapidarc their resulting DVHs shown in figure 2 for head-neck cancer and figure 4 for the pelvic plan are close to a single line.

CONCLUSIONS

Based on the extensive analysis and discussions of the measured data presented in this study, as well as consistency with other studies on beam matching, we concluded that the three Varian Clinac-iX are dosimetrically matched. As a direct clinical impact, in case of sudden interruption or during periodic preventive maintenance of the Clinacs-iX, immediate interchange of patients between linear accelerators is possible without need to re-plan.

ACKNOWLEDGEMENTS

Thanks to laboratory of optoelectronics and devices of University Ferhat Abbas Sétif 1 (Algeria) and Radiation therapy center in Setif (Algeria) for making available to us the use of the equipment required in our study.

***Ethical considerations*:** None.

***Funding*:** This study has been partially supported by the Ministry of Higher Education and Scientific Research (Ministère de l'enseignement supérieur et de la recherche scientifique: project CNEPRU B00L02UN190120190007) and the laboratory of optoelectronics and devices of University Ferhat Abbas Sétif 1 (Algeria).

***Conflicts of interests*:** Declared none.

***Author Contribution*:** (S.K) and (Z.C) contributed equally in this work.

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[DOI: 10.52547/ijrr.20.3.25]