RESEARCH ARTICLE

Dosimetric Validation of Volumetric Modulated Arc Therapy with Three 6MV Beam-Matched Linear Accelerators

Sangaiah Ashokkumar[1,2]*, K M Ganesh[1,3], K Ramalingam[1,2], K Karthikeyan[1,2], N Jagadheeskumar[2]

Abstract

Background: To avoid inconvenience to patients due to linear accelerator down time in busy radio-therapy departments, treatment plans can be switched between linear accelerators provided that all exhibit the same same dosimetric characteristics. In other words linear accelerators should be beam-matched. **Aim:** The aim of this study was to evaluate the clinical significance of beam-matching using VMAT plans. **Materials and Methods:** Dosimetric data with a 6MV beam from am Clinac 2100CD were taken as baseline values and other two units, a 2300CD and a Unique Performance, were factory tuned in accordance. An analysis of PDD data was performed for different field sizes to evaluate energy matching. Beam profiles for field sizes of 10×10 cm^2 and 40 × 40 cm^2 at depths of 1.5 cm and 10 cm were analyzed. The relative output factor and MLC dosimetric properties were compared with each machine to determine variability among the different models. Thirty patients from our database were selected, ten each for head and neck, thorax and pelvis sites. VMAT plans were created in the Eclipse treatment planning system for a Clinac 2100 CD for reference. and verification plans were created for each to compare point dose measurements. **Results:** The TPR 20/10 for 10 × 10 cm^2 was well matched, showing no energy differences. Deviation of all point dose measurements fell within ±3%. Planar dose maps all showed greater than 95% of points with a passed area γ-value less than 1. **Conclusion:** Our study evaluation of beam matching with treatment planning modeling showed good agreement fior 6 MV beams across all three linear accelerators used in our clinical environment.

Keywords: VMAT- AAA- TPS- beam matching- 2300CD- 2100CD- unique performance

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Introduction

To avoid inconvenience to the patient due to linear accelerators down time in busy radio therapy department, the patient treatment plan can be switched between any one of department's linear accelerators without change in patients treatment plan provided all the accelerators exhibits same dosimetric characteristics. In other words the liner accelerators should be beam matched (Sjostrom et al., 2009). The dosimetric parameters like percentage depth dose (PDD), profiles measured in different depths and output factors are considered as criteria for beam matching.

The beam data measurement results from the commissioning of three linear accelerators from the same manufacturer Varian medical systems (Varian Medical Systems, Palo Alto, CA). Machine models are Clinac 2100CD, Clinac 2300CD and Unique Performance (this machine will be called as Unique in the rest of the paper). This study was performed to identify and evaluate any differences in the beam characteristics between these machines and to evaluate the beam matching for standard 6 MV beam. An analysis of the beam data was then performed to evaluate the reproducibility of the results and the possibility of "beam matching" between the three linear accelerators.

In the recent past, a new technology in radiotherapy called Volumetric Modulated Arc Therapy (VMAT) technique has emerged. Volumetric modulation is achieved by varying gantry speed, multileaf collimator (MLC) positions and dose rate simultaneously while beam is ON (Otto, 2008).

Although the previous studies (Watts, 1999; Cho et al., 2005; Hrbacek et al., 2007; Beyer, 2013; C. Krishnappan et al., 2016) shown the possibility of beam matching, but there is lack of studies addressing the clinical significance of beam matching. The equivalence of treatment plan modeling with beam data from each linear accelerator type is necessary to determine the range of clinical significance.

*[1]Research and Development Center, Bharathiar University, Coimbatore, [2]Department of Radiation Oncology, Yashoda Hospitals, Secunderabad, [3]Department of Medical Physics, Kidwai Memorial Institute of Oncology, Bengaluru, India. *For Correspondence: ashoksamus@gmail.com*

Materials and Methods

This study has been bifurcated for convenience. The first section compares the beam data from three beam matched linear accelerators. The second section compares the equivalence of treatment plan modeling to determine the clinical significance of beam-matching.

A. Linear accelerator beam data comparison

Three machines which are available in our department are installed in different time periods. Clinac 2100CD was installed in June 2004, Clinac 2300CD was installed in Jan 2009 and unique performance machine (this machine will be called as Unique in the rest of the paper) was installed in January 2015. All these three machines are equipped with Millennium 120 Multileaf Collimator (MLC) and capable of delivering VMAT.

In beam matching approach, 6MV beam of all these accelerators are factory tuned in such a way that the dosimetric characteristics meet the reference values within a specified interval. The dosimetric data of Clinac 2100 CD was taken as baseline value and other units are tuned with respect to that. As per Customer Acceptance Procedure (CAP), 2300CD and unique machine's 6MV photon characteristics (energy, flatness-symmetry, and penumbra) have to be within ±1% of 2100 CD machine's data.

Beam data commissioning were done on three linear accelerators by measuring percent depth doses (PDDs), beam profiles, and output factors. No attempt to match the beam parameters were made after installation of these linacs. Measurements for all three linear accelerators were performed using a CC13 (0.13cc) ion chamber and radiation field analyzer. The chamber was offset to the effective point of measurement (0.6*rcav) for all PDD and profile measurements as per Technical Report Series (TRS) no-398.

The resulting dosimetric dataset from each linear accelerator were compared with other two linacs. PDD data were analyzed for different field sizes 4 × 4 cm^2, 10×10 cm^2, and 40 × 40 cm^2 to evaluate the energy match. Beam profile data for field sizes 10×10 cm^2 and 40 × 40 cm^2 at depths 1.5cm and 10cm were analyzed. The relative output factor measurements and MLC dosimetric properties were compared between each machine to determine the variability among different models.

B. Plan Quality comparison

In plan quality comparison study, previously treated thirty patients were selected. Sites included were head and neck, cervix and thorax with ten patients for each site. For all patients, VMAT plans were generated in Eclipse Treatment Planning system (version 11.0) using Progressive Resolution Optimizer (PRO)- III algorithm and doses were computed using Anisotropic Analytic Algorithm (AAA) with a calculation grid size of 0.25cm (Breitman et al ., 2007; Hrbacek et al., 2011). VMAT plans created for Clinac 2100CD machine was taken as a reference plan for the comparison. Without re-optimization, the doses were recalculated on clinac 2300CD and unique machine with fixed MUs as of 2100CD machine plan.

1) Plan comparison parameters: For all thirty patients, Planning Target Volume (PTV) mean dose, maximum dose and body maximum dose were compared. For organs at risk (OAR), mean doses are compared for parallel structures and maximum doses for serial structures.

2) Measured Dose Comparison: Point dose and planar dose measurements were done for all 30 patients in all three machines. For point dose measurements, verification plans have been created on slab phantom with ion chamber CC13 (0.13cc) to measure the point dose at isocenter. In order to reduce the measurement uncertainty, we used same slab phantom, chamber (CC13), electrometer (CDX2000B) and extension cable in all measurements. For planar dose measurements, verifications plans were created on the Multicube phantom with Imatrix (IBA Dosimetry) for all three machines. TPS dose calculated on 2100CD machine is taken as reference for all measurements and variation from 2100CD measured dose noted. The 2100CD machine's verification plans have been beamed ON in all three machines by doing machine override option available in 2300CD and Unique machine consoles.

Results

A. Linear accelerator beam data comparison

An analysis of percent depth dose (PDD) data was performed to evaluate the energy match. The depth of dose maximum (dmax), PDD at 10 cm (PDD10cm) and PDD at 20 cm (PDD20cm) were evaluated for three field sizes: 4 × 4 cm^2, 10 × 10 cm^2, and 40 × 40 cm^2. An energy parameter Tissue Phantom Ratio (TPR20/10) value was obtained. The results were tabulated in Table 1.

The measured cross plane beam profiles were compared. Beam profile penumbra and the field size definition at depths 1.5 cm and 10 cm were evaluated and results were shown in Table 2.

Output factors for different field sizes ranging from 4x4 cm^2 to 40 x40 cm^2 were obtained in SAD technique at 5 cm depth along central axis and normalized to 10 x 10 cm^2 field size to get the relative output factor

Table 1. Energy Match Analysis

Data	Field size (cm)	2100 CD	2300 CD	Unique	Average	SD
d_{max} (cm)	4x4	1.5	1.66	1.37	1.51	0.15
	10x10	1.4	1.58	1.39	1.46	0.11
	40x40	1.14	1.32	1.16	1.21	0.1
PDD_{10cm}	4X4	62	62.1	61.4	61.83	0.38
	10X10	66.5	67.1	66.4	66.67	0.38
	40X40	71.6	71.6	71.5	71.57	0.06
PDD_{20cm}	4X4	33.7	33.9	33	33.53	0.47
	10X10	38.2	38.6	38	38.27	0.31
	40X40	45.8	45.5	45.8	45.7	0.17
$TPR_{20/10}$	4X4	0.63	0.63	0.62	0.63	0.01
	10X10	0.67	0.67	0.67	0.67	0
	40X40	0.75	0.75	0.75	0.75	0

SD, Standard Deviation

Table 2. Beam Profile Analysis

Depth	Linear Accelerator	10cmX10cm Field size		40cmx40cm Field size	
		Penumbra(mm)	Field width(cm)	Penumbra(mm)	Field width(cm)
1.5 cm	2100CD	5.4	10.14	5.6	40.2
	2300CD	5.6	10.2	5.5	40.9
	UNIQUE	5.5	10.18	5.6	40.93
10 cm	2100CD	6.8	11.1	9.9	43.6
	2300CD	6.9	11.1	9.8	44.2
	UNIQUE	7	11.05	9.5	44.3

Table 3. Relative Output Factor

				Percentage of Deviation	
Field size	2100CD	2300CD	Unique	2100 vs. 2300	2100 vs. unique
4X4	0.8993	0.872	0.918	3.04	-2.08
8X8	0.9763	0.954	0.98	2.28	-0.38
10X10	1	1	1	0	0
15X15	1.0406	1.0316	1.035	0.86	0.54
25X25	1.0875	1.0776	1.076	0.91	1.06
30X30	1.1062	1.0979	1.088	0.75	1.65
35X35	1.119	1.1156	1.098	0.3	1.88
40X40	1.1297	1.1316	1.102	-0.17	2.45

Table 4. MLC Parameters

Machine	MLC Transmission	Dosimetric Leaf Gap
2100CD	1.45%	0.2cm
2300CD	1.40%	0.2cm
UNIQUE	1.15%	0.17cm

which is tabulated in Table 3.

A1. MLC parameters

MLC transmission which includes both inters leaf and intra leaf transmissions and dosimetric leaf gap of all machines have been tabulated in table 4.To compare the MLC properties dosimetrically, a plan has been created in TPS with MLC strips of sizes 0.5mm, 1mm, 2mm, 5mm, 10mm and 15mm. The plan is delivered in all three machines and point dose at 5cm depth is measured using CC13 chamber in slab phantom. The measured doses are compared with TPS calculated dose of 2100CD machine. Tables 5 show the deviation between the measured and calculated doses for all three machines.

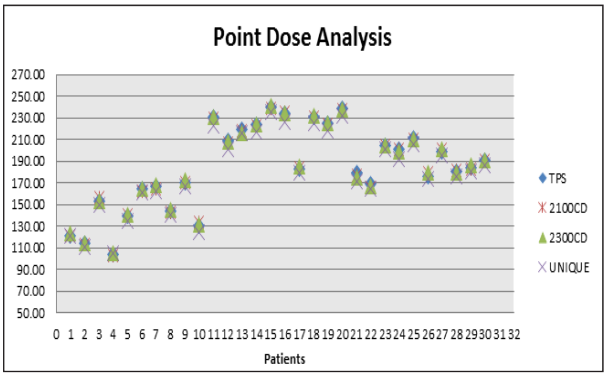

Figure 1. Point Dose Analysis of Three Machines

B. Plan Quality comparison

B1 Open field Measurements

To check the clinical correlation of beam matching of 6MV beam in all three machines, open fields 10x10 cm^2 and 20x20 cm^2 have been calculated on CT data of Multicube Phantom with I- Matrix (iba) in Eclipse TPS (V-11) for the beam 6MV in 2100CD machine. The same plans have been delivered in all three machines

Table 5. MLC Stripping Field Dose Deviation

DLS	TPS Dose 2100CD	Measured Dose (cGy)			Dose Deviation (cGy)		
	(cGy)	2100CD	2300CD	Unique	2100CD	2300CD	Unique
0.5 mm	15.4	15.96	17.47	15.3	0.56	2.07	-0.1
1 mm	17.6	18.16	19.51	17.79	0.56	1.91	0.19
2 mm	22	22.25	23.87	22.45	0.25	1.87	0.45
5 mm	34.6	34.85	36.68	34.53	0.25	2.08	-0.07
10 mm	54.1	54.47	55.9	54.08	0.37	1.8	-0.02
15 mm	88.2	88.43	90.54	88.06	0.23	2.34	-0.14

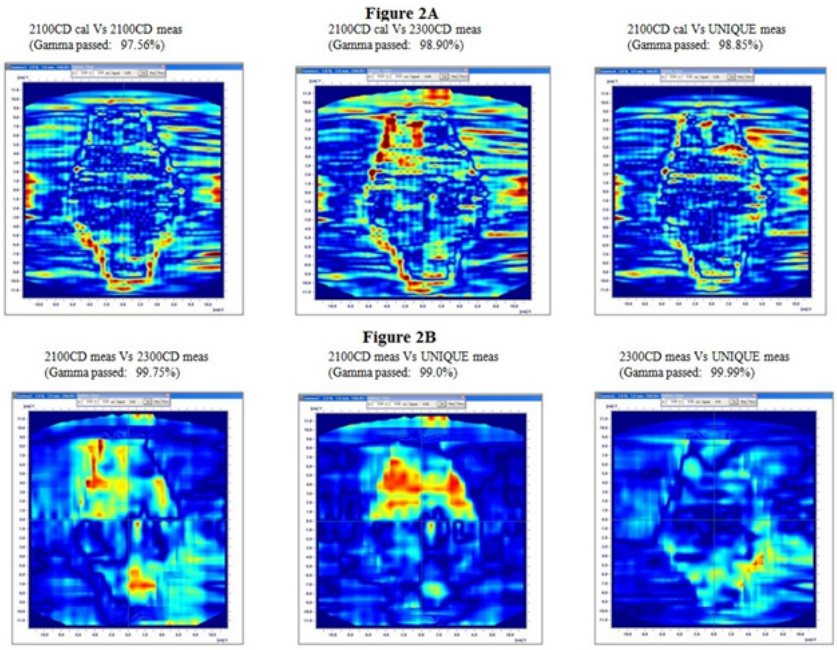

Figure 2. Gamma Analysis for 3% Dose Difference and 3mm Distance to Agreement Criteria

Table 6. p -values for Head and Neck Cases

	p-Value						
	Spine Max Dose	PRV Spine Max Dose	Brain Stem Max Dose	Lt. Parotid Mean Dose	Rt. Parotid Mean Dose	Body Mean Dose	PTV Mean Dose
2100CD Vs 2300CD	0.311	0.743	0.953	0.948	0.917	0.901	0.426
2100CD Vs Unique	0.472	0.362	0.873	0.348	0.323	0.828	0.264
2300CD Vs Unique	0.022	0.223	0.828	0.384	0.38	0.794	0.072

using the same Phantom arrangements and dose maps in detector plane were acquired in all three machines using omnipro-IMRT Software (iba). The gamma analysis has been done with criteria of 3% Dose Difference (DD) and 3mm Distance to Agreement (DTA) for measured open fields between all three machines resulted in a passing rate greater than 99.0% for all open fields.

B.2 VMAT plan comparison

Clinically accepted VMAT plans of all 30 patients done on 2100CD machine have been recalculated on 2300CD and unique Performance machines with fixed MUs. Dose distribution in all three machines for PTV was acceptable to the clinical goal and OAR doses were also within the tolerance doses for each. The statistical significance of difference for all parameters were tested between each machine pair using student's t-test at 95% confidence limit and resulted p- values were tabulated. The p-values for all machine pairs and all parameters were tabulated in Table 6, 7 and 8 for H and N, Thoracic and Pelvic patients respectively.

For H and N VMAT plans, Spine max dose, PRV Spine max dose, left parotid mean dose, right parotid mean dose, body mean dose and PTV mean doses were compared. For pelvic VMAT plans rectum mean dose, bladder mean dose, bowel mean dose, left and right head of femur mean dose, body mean dose and PTV mean doses were compared. For thorax VMAT plans, Spine max dose, PRV Spine max dose, left lung mean dose, right lung mean dose, body mean dose and PTV mean doses were compared.

Table 7. p -values for Thorax Cases

	p-Value					
	Spine	PRV Spine	Left Lung Mean Dose	Right Lung Mean	Mean Body	PTV Mean
2100CD Vs 2300CD	0.8745	0.8519	0.9729	0.9822	0.9599	0.864
2100CD Vs Unique	0.8068	0.8022	0.8557	0.9238	0.8032	0.8374
2300CD Vs Unique	0.6885	0.6626	0.8294	0.9062	0.7647	0.7066

Table 8. p -values for Pelvic Cases

	p-Value						
	Rectum	Bladder	Bowel	LT.Hof	RT.Hof	Mean Body	PTV Mean
2100CD Vs 2300CD	0.576	0.707	0.904	0.255	0.916	0.958	0.042
2100CD Vs Unique	0.673	0.687	0.898	0.407	0.384	0.995	0.094
2300CD Vs Unique	0.341	0.437	0.799	0.569	0.332	0.96	0.001

B3.Patient specific Quality Assurance

B.3.1 Point Dose Verification

VMAT verification plans were created for all thirty patients and the doses were measured using CC13 chamber. Figure 1 shows the matching of measured point doses at isocenter for all thirty patients in three machines with reference 2100CD TPS calculated dose. Dose deviation between the TPS calculated reference values and measured values are well within the tolerance of ±3%.

B.3.2 Planar Dose Verification

For the gamma analysis the passing criteria set it as 3% DD and 3mm DTA for 95% of points should pass gamma less than one. The findings are reported as Mean ±1 Standard Deviation (SD). The result of TPS calculated (2100CD) versus measured dose in 2100CD, 2300CD and Unique machines are 96.43±1.21%, 96.51±1.12% and 96.32±1.52% respectively. The results of 2100CD measured versus 2300CD measured is 97.28±1.44%.for 2100 measured versus Unique measured is 97.92±1.40 and 2300 CD measured versus Unique measured is 97.91±1.18.

Discussion

Table 1 shows the TPR20/10 of reference field size 10x10 cm^2 of three accelerators are well matching showing no energy difference. Table 3 shows the output factor analysis where the differences were within ±3%.

The unique machine has less MLC transmission (Table 4) compare to other machines which resulted in good agreement of measured stripping field dose with TPS predicted dose (Table 5).

From Table 7, all the p-values are greater than the significant value 0.05 except spine max dose between 2300CD and Unique which is having p-value 0.022. But the absolute dose of spinal cord maximum dose is well within the tolerance dose 4500cGy for all ten H and N patients.

In thoracic cases, the deviations in OAR and PTV mean doses are very less and are statistically insignificant for all 10 patients in all three machines.

For pelvic cases, all the p-values are greater than the significant value of 0.05 (table 8) except PTV mean dose between 2300CD versus Unique and 2100CD versus 2300CD which are having p-value 0.001 and 0.042 respectively. But the absolute dose analysis shows 95% of PTV volume is receiving 95% of prescribed dose which is clinically accepted. Variations in OAR doses are insignificant statistically and also clinically accepted.

Figure 2 shows the sample gamma analysis for a pelvis case. It shows that planar dose maps of measured versus measured (figure 2B) were in good agreement compared to measured versus calculated (figure 2A) in TPS due to the resolution of the Imatrix detector is 0.76cm but the calculation grid size used in eclipse TPS is 0.25 cm.

We found no systematic dose deviation for any structure studied in any machine even though there is systematic deviation in open field output between different machines.

To sum it up, in our study 15 beam profiles were compared, 90 point dose measurements data were compared and the deviation of all point dose measurements fell within ±3%. Ninety planar dose maps were measured and compared and all of them have shown greater than 95% of points passed area γ-value less than 1.

This study is limited for medium (5x5cm^2) to large (25x25 cm^2) field sizes. Smaller field sizes (less than 4x4 cm^2) which are widely used in stereotactic treatments are not validated in this study.

In conclusion, the comparison of dosimetric parameters like PDDs, profiles, and output factor shows the reproducibility of photon beam in beam matched linear accelerators. The dosimetric analysis of VMAT head and neck, thorax and pelvis plans swapped between three machines are well within clinical acceptable limits. The evaluations of Beam matching with pre-verification plans are in good agreement with the 6 MV beams of all three linear accelerators. These results support the swapping of patient across beam-matched linear accelerators in busy clinical environment without replanning of VMAT plans to manage the machine down times. Care must be taken to ensure the verification of beam matching prior to implementation.

Statement conflict of Interest

Authors have no conflict of Interest.

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