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Trajectory log file sensitivity: A critical analysis using DVH and EPID

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ABSTRACT

Aim: The aim of this study was to investigate the sensitivity of the trajectory log file based quality assurance to detect potential errors such as MLC positioning and gantry positioning by comparing it with EPID measurement using the most commonly used criteria of 3%/3 mm.
Materials and methods: An in-house program was used to modified plans using information from log files, which can then be used to recalculate a new dose distribution. The recalculated dose volume histograms (DVH) were compared with the originals to assess differences in target and critical organ dose. The dose according to the differences in DVH was also compared with dosimetry from an electronic portal imaging device.
Results: In all organs at risk (OARs) and planning target volumes (PTVs), there was a strong positive linear relationship between MLC positioning and dose error, in both IMRT and VMAT plans. However, gantry positioning errors exhibited little impact in VMAT delivery. For the ten clinical cases, no significant correlations were found between gamma passing rates under the criteria of 3%/3 mm for the composite dose and the mean dose error in DVH ($r < 0.3$, $P > 0.05$); however, a significant positive correlation was found between the gamma passing rate of 3%/3 mm (%) averaged over all fields and the mean dose error in the DVH of the VMAT plans ($r = 0.59$, $P < 0.001$).
Conclusions: This study has successfully shown the sensitivity of the trajectory log file to detect the impact of systematic MLC errors and random errors in dose delivery and analyzed the correlation of gamma passing rates with DVH.

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1. Background

In conventional radiation therapy, techniques such as 3D conformal radiotherapy (3DCRT) deliver a sufficient dose to the tumor volume while sparing critical organs adjacent to it. To achieve this, the linear accelerator is equipped with multileaf collimators (MLC) to shape the radiation field to conform to the tumor volume while shielding normal healthy tissue. In modern radiotherapy equipment, complex techniques, such as intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT), are capable of delivering a much higher conformal dose to the tumor volume than can be achieved with 3DCRT, while still being able to spare nearby critical organs. In IMRT and VMAT, this is made possible by the use of dynamic MLC (sliding window), with each leaf of the MLC being able to constantly change its position to modulate the desired dose distribution while the radiation is on. By comparison, the MLC in 3DCRT are static during delivery. Therefore, both IMRT and VMAT are capable of generating a very steep dose gradient between the tumor and the healthy normal tissue. However, any deviation in the actual MLC position from its planned position can affect the accuracy of the dose delivery, and such errors can occur due to deterioration in the performance of each MLC motor.[1] The main difference between IMRT and VMAT is that each treatment field has a fixed gantry angle in IMRT, whereas in VMAT the gantry rotates continuously around the patient while the MLC modulates the radiation beam. Therefore, any deviation in the actual gantry position from that planned will affect the accuracy of the dose delivery from VMAT. The additional contribution of delivery parameters, such as the speed of gantry rotation, make VMAT delivery more complex than IMRT, and therefore, more susceptible to inaccuracies in dose delivery. To prevent such errors from happening during IMRT/VMAT delivery, patient specific quality assurance is performed before the actual delivery, to ensure that the calculated and measured doses agree, thereby indicating that all planned parameters are delivered within the tolerance limits.

Within our department, the currently implemented methods for patient specific quality assurance for IMRT/VMAT verification are point dose absolute measurement and 2D planar dose verification using an electronic portal imaging device (EPID), following the guidance of the American Association of Physicists in Medicine (AAPM) Task Groups 119 and 120,[2,3] The total dose in each treatment field of the IMRT or VMAT plan is delivered to a water equivalent slab phantom and measurement is performed using an ion chamber. For an IMRT or VMAT dose delivery to be considered accurate, the measured point dose must agree with the calculated point dose to within 3% using a point dose absolute measurement method.[2,3] A second method for the verification of an IMRT or VMAT plan is to deliver each treatment field to an EPID, and then use gamma analysis to compare the 2D predicted dose calculated by the Treatment Planning System (TPS) with the measured dose distribution. For IMRT or VMAT to be considered accurate, at least 90% of the 2D dose distribution delivered by each treatment field must agree with the predicted 2D dose distribution calculated by the TPS to within a 3% dose difference and a 3 mm agreement in distance.[2,3]

However, in a study described by Dong et al.,[4] it was reported that point dose measurements performed on 751 IMRT plans contained errors ranging from −12.7% to 11.7%. This was because IMRT delivery usually consists of a large number of fields, each of which is smaller than the size of the ion chamber; this can result in partial volume effects, which is one reason for such a large range of errors, as discussed in the ICRU Report 83.[5] Kruse et al.[6] also demonstrated that performing gamma analysis on per-field measurements using EPID does not guarantee dosimetric accuracy, and furthermore, Zhen et al.[7,8] also reported that the gamma passing rate only indicates the quantity of errors; it does not provide information on the location and magnitude (dose) of errors, which is clinically important. Therefore, there is a need for a new method for verifying the accuracy of IMRT and VMAT deliveries in clinically relevant terms, such that the actual patient dose can be investigated; several authors[9–14] have described methods for doing this. Patient specific quality assurance using the linear accelerator (linac) log file to generate a dose-volume histogram (DVH) of the patient during the actual delivery allows the possibility of monitoring the average MLC positional errors,[15–20] as well as providing information on the accuracy of the dose delivery to the patient's target and critical organ structures.

The aim of this study was to investigate the sensitivity of trajectory log file based Quality Assurance (QA) by introducing actual delivery parameters (random errors) and systematic errors in MLC and gantry position using in an house program. The sensitivity of the trajectory log file was analyzed by comparing original TPS calculated plan vs. error induced plan for both IMRT and VMAT. The potential of trajectory log file QA was detected by comparing 2D measured dose distribution with zero error vs. measured dose distribution with induced error. In addition, the trajectory log files were used to reconstruct the error induced plan and recalculated in TPS to assess the dose difference obtained in DVH by comparing it to the original plan. The in-house program works by entering the actual delivery parameters (e.g. MLC position, jaw tracking position, cumulative dose index (or fractional MU per control point), and gantry angle) recorded in the trajectory log files into the treatment plan. The new treatment plan with replaced parameters is then imported into the TPS to recalculate a new dose distribution for the tumor volume.

2. Materials and methods

2.1. A linear accelerator and treatment planning system

This study employed similar methods to those used in a previous study by Betzel et al.[21] All IMRT and VMAT plans were generated using a Varian Eclipse TPS using Anisotropic Analytical Algorithm (AAA) for dose calculation and optimized using Dose Volume Optimizer (DVO) and Progressive Resolution Optimizer (PRO) Version 13.0.26 (all produced by Varian Medical Systems, Palo Alto, CA). All calculated plans were delivered with a Varian TrueBeam Version 2.0 equipped

with a Millennium 120 leaf MLC (Varian Medical Systems) capable of performing Jaw tracking. For portal dosimetry, a two-dimensional predicted dose distribution was generated for each field in IMRT/VMAT plan using the Portal Dose Imager Prediction (PDIP) algorithm Version 13.0.26 (Varian Medical Systems). Measurements were delivered to an amorphous silicon portal imager (S1000 IDU 20; Varian Medical Systems, Palo Alto, CA) with a dimension of 401×301 mm and 1024×768 pixels.

2.2. Trajectory log file

The trajectory log file (Version 3.0) was generated after delivery of the plan had been completed. During the plan delivery, the TrueBeam system is capable of continuously recording all delivery parameters, such as positioning of MLC, Jaw tracking position, gantry angle, and cumulative dose index (or fractional MU per control point); this is performed at a sampling interval of 20 ms with the data saved in a binary format in the created log file.

2.3. Patient selection and treatment plan

Three head and neck and three prostate cases were used in this study to evaluate the sensitivity of trajectory log files in detecting systematic errors and comparing it with EPID dosimetry. Each of the plans was copied and reoptimized with the same planning objectives to generate both IMRT and VMAT plans, respectively. A prescription dose of 70 Gy in 33 fractions for head and neck cases and 70 Gy in 28 fractions for prostate cases were used to generate the plans. In total, 90 treatment plans were created as a result of introducing systematic MLC and gantry position errors into 12 original plans.

In addition, a total of 5 IMRT and 5 VMAT clinical approved cases were selected for study of sensitivity of trajectory log files in detecting random errors and comparing it with EPID dosimetry. The disease locations in 5 VMAT clinically approved plans were the brain, cervix, pancreas, rectum, and lung, and in 5 IMRT clinically approved plans, the thyroid (twice), nasopharynx, prostate, and nasal cavity. All VMAT plans were generated with 2.5 arcs, except for the lung case which used 2 partial arcs. All IMRT plans were generated using 9 fields, except for the nasal cavity plan, which used only 7 fields. All treatment plans were generated using 6 MV photon beams at a dose rate of 600 MU min^{-1}; however, the dose rate varies during IMRT or VMAT delivery taking into account the speed of the MLC movement and the speed of which the gantry rotates for VMAT delivery. Each field of a IMRT plan consisted of 166 control points, resulting in a total of 1494 control points for a 9 field IMRT treatment plan. Each full arc of a VMAT plan consisted of 177 control points at about 2° per control point. Each control point consisted of a sub-field that contained several important parameters such as the position of each individual leaf in the MLC, gantry angle, jaw position, and cumulative dose index (or fractional MU per control point).

2.4. Systematic and random errors

Both IMRT and VMAT plans were exported in DICOM RT format from the TPS to an external computer, which contained an in-house program developed with Python programming language (The Scientific Python Development Environment, Version 2.7+, The Spyder Development Team, http://www.Python.org/) for plan modification.

Systematic induced errors on IMRT and VMAT delivery parameters were necessary in order to study the impact on dose differences found in target and critical organs DVH metrics. The systematic errors resulted in an opening of the MLC of 0.25, 0.5, 0.75, and 1 mm and were introduced for the entire bank A, with additional systematic errors of 0.25°, 0.5°, 0.75°, and 1° in the gantry position (clockwise direction) induced for VMAT cases. A copy of all the IMRT/VMAT original plans was sent to an external computer for introduction of systematic errors using the Python script, these modified plans were imported back into the Eclipse TPS for recalculation.

As for all IMRT and VMAT clinically approved plans used in this study for evaluating the sensitivity of trajectory log files have random errors, a copy of all the IMRT/VMAT original plans was sent to an external computer for introduction of actual information recorded in the log files during treatment delivery using the Python script, these modified plans were imported back into the Eclipse TPS for recalculation. To evaluate the systematic and random errors, the recalculated patient DVH was then compared with the original DVH to assess the differences in target and critical organ dose.

2.5. Quantitative data analysis

Pearson's correlation coefficient (r) was used to statistically analyze the relationship between gamma passing rate and changes in DVH, and a P-value of <0.05 was necessary to conclude that the variables were correlated. An r value of 0–0.39 was regarded as a weak correlation between %GP and %DE, 0.4–0.59 as moderate, 0.6–0.79 as strong and 0.8–1 as very strong.

To evaluate the impact of MLC positioning errors on the dose differences found in DVH metrics, the original plans were copied and edited with the actual delivered parameters (random errors) from the trajectory log files or edited with systematic errors using Python for recalculation. To quantitatively analyze the following parameters, these recalculated plans were then compared with the original plans by using the average of mean dose (Dmean), near-minimum dose (D98%), and near-maximum dose (D2%) for the planning target volume (PTV) and organ at risk (OAR), as shown in the DVH. The average absolute dose differences between the recalculated plan and original plan were reported as dose error (%), as shown in the following equation[8]:

$$\text{Dose Error (\%)} = \frac{\text{Recalculated plan dose (cGy)} - \text{Original plan dose (cGy)}}{\text{Original plan dose (cGy)}} \times 100$$

These average dose errors were then plotted against MLC positioning errors. In addition, the average dose error and standard error found in DVH between the original plan and recalculated plan with MLC positioning error are listed in Table 1 for prostate cases and Table 2 for head and neck cases.

Table 1 – The average dose error (%) in DVH metrics between original and recalculated plan of three prostate cases using actual delivery parameters with MLC-induced errors for OARS and PTV have been shown.

		Organ at risk												Planning target volume					
		Bladder						Rectum						Prostate					
		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)	
	MLC error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
Prostate cases	0.25 mm	1.10	0.51	0.46	0.14	0.73	0.22	0.94	0.13	0.62	0.11	0.97	0.20	0.82	0.09	0.49	0.14	0.52	0.10
	0.50 mm	2.30	0.93	1.04	0.28	1.54	0.40	1.74	0.28	1.22	0.20	1.94	0.41	1.62	0.19	1.03	0.27	1.03	0.20
	0.75 mm	3.32	1.35	1.70	0.46	2.33	0.57	2.59	0.43	1.79	0.30	2.91	0.62	2.38	0.30	1.57	0.42	1.54	0.30
	1.00 mm	4.38	1.73	2.41	0.68	3.13	0.75	3.45	0.58	2.34	0.38	3.88	0.84	3.06	0.41	2.33	0.59	2.04	0.40
		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)	
	MLC error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
Prostate cases	0.25 mm	0.11	0.87	1.01	0.14	0.84	0.07	0.68	0.10	1.4	0.14	1.02	0.04	0.81	0.44	1.75	0.59	0.99	0.07
	0.50 mm	0.95	1.07	1.86	0.19	1.67	0.14	1.50	0.14	2.6	0.25	2.06	0.08	1.70	0.61	2.60	0.85	1.70	0.15
	0.75 mm	1.77	1.26	3.02	0.16	2.50	0.22	2.31	0.19	3.78	0.57	3.09	0.13	2.59	0.80	3.47	1.13	2.41	0.23
	1.00 mm	2.63	1.47	4.24	0.10	3.33	0.29	3.11	0.24	5.09	0.86	4.12	0.17	3.48	1.01	4.39	1.37	3.12	0.31

Table 2 – The average dose error (%) in DVH metrics between original and recalculated plan of three head and neck cases using actual delivery parameters with MLC-induced errors for OARS and PTV have been shown.

		Organ at risk												Planning target volume					
		Brainstem						Spinal cord						Nasopharynx					
		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)		IMRT (D98%)		IMRT (D2%)		IMRT (Dmean)	
	MLC error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
H&N cases	0.25 mm	1.26	0.18	1.04	0.24	1.33	0.20	1.12	0.77	2.13	0.12	1.98	0.18	0.81	0.13	0.49	0.14	0.52	0.10
	0.50 mm	2.52	0.36	2.06	0.44	2.66	0.40	2.32	1.18	4.23	0.23	3.93	0.36	1.63	0.27	1.03	0.27	1.03	0.20
	0.75 mm	3.78	0.56	3.11	0.59	3.99	0.60	3.00	1.55	6.30	0.33	5.89	0.54	2.44	0.40	1.57	0.42	1.54	0.30
	1.00 mm	5.03	0.75	4.14	0.73	5.29	0.81	4.42	2.23	8.35	0.41	7.84	0.72	3.23	0.53	2.33	0.59	2.04	0.40
		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)	
	MLC error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
H&N cases	0.25 mm	−0.89	0.60	0.07	0.07	0.25	0.09	1.12	0.56	2.59	0.45	1.20	0.15	0.51	0.55	1.75	0.59	0.99	0.07
	0.50 mm	−0.58	0.64	0.18	0.10	0.60	0.08	1.78	0.90	4.61	0.92	2.31	0.24	1.38	0.89	2.60	0.85	1.70	0.15
	0.75 mm	−0.26	0.68	0.28	0.14	0.95	0.07	3.75	0.31	6.62	1.40	3.41	0.33	2.23	1.24	3.47	1.13	2.41	0.23
	1.00 mm	0.05	0.73	0.39	0.19	1.29	0.06	5.45	0.41	8.63	1.88	4.53	0.43	3.08	1.60	4.39	1.37	3.12	0.31

Table 3 – The average dose error (%) in DVH metrics between original and recalculated plan of three prostate and head and neck cases using actual delivery parameters with gantry-induced errors for OARS and PTV have been shown.

		Organ at risk												Planning target volume					
		Bladder						Rectum						Prostate					
		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)	
	Gantry error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
Prostate cases	0.25 deg	−0.65	0.57	0.22	0.18	−0.01	0.05	−0.13	0.11	0.54	0.10	−0.02	0.07	−0.30	0.29	0.91	0.35	0.27	0.02
	0.50 deg	−0.51	0.46	0.23	0.20	−0.03	0.05	−0.12	0.11	0.47	0.13	−0.02	0.10	−0.30	0.34	0.93	0.33	0.28	0.02
	0.75 deg	−0.43	0.29	0.27	0.19	−0.04	0.06	−0.11	0.12	0.44	0.13	−0.03	0.14	−0.32	0.41	0.96	0.32	0.28	0.02
	1.00 deg	−0.41	0.22	0.30	0.18	−0.06	0.07	−0.10	0.13	0.44	0.11	−0.03	0.17	−0.38	0.45	0.99	0.32	0.29	0.03

		Brainstem						Spinal cord						Nasopharynx					
		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)		VMAT (D98%)		VMAT (D2%)		VMAT (Dmean)	
	Gantry error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error	Avg	Standard error
H&N cases	0.25 deg	−1.26	0.59	−0.04	0.02	−0.09	0.11	0.00	0.00	0.75	0.28	0.10	0.05	−0.52	0.29	0.56	0.27	0.18	0.05
	0.50 deg	−1.28	0.61	−0.04	0.03	−0.08	0.12	0.27	0.27	0.91	0.33	0.10	0.05	−1.13	0.50	0.57	0.29	0.17	0.04
	0.75 deg	−1.31	0.64	−0.04	0.05	−0.07	0.13	0.27	0.27	1.07	0.38	0.10	0.07	−2.13	0.64	0.57	0.31	0.16	0.04
	1.00 deg	−1.33	0.65	−0.06	0.07	−0.07	0.13	0.46	0.24	1.22	0.42	0.11	0.08	−3.22	1.02	0.55	0.33	0.13	0.03

For the VMAT plans, the effect of gantry positioning error on the dose differences in DVH and standard error was also reported in Table 3. Linear fitted line models were used to study the impact of gantry angle and MLC positioning on the dose differences, with the slope of the linear fitted line indicating the magnitude of dose error in % mm^{-1} due to MLC positioning errors, and dose error in % deg^{-1} due to gantry positioning errors.

Deviations in DVH between the original plans and those recalculated with replaced parameters from the linac log files parameters were expressed as dose error (%). Box and whisker plots representing the dose error (%) in the OARs and PTVs in terms of D98%, Dmean, and D2% were then plotted against gamma passing rate (%) averaged over all fields, and the composite dose of all fields under the criteria of 3%/3 mm as shown in Fig. 5. In portal dosimetry analysis for both IMRT and VMAT, the average gamma passing rate is the average of gamma passing rate per-field and the composite dose is the sum of all field doses. Furthermore, Pearson's R-correlation tests were used to investigate the relationship between the gamma passing rate (%) and mean DVH dose error in all of the 10 randomly chosen IMRT and VMAT treatment plans.

2.6. *Correlation of gamma passing rate with systematic errors*

In this part of the study, the measured dose differences were investigated and correlated with the calculated dose differences described in the previous section. Original and modified plans with systematic errors were delivered to EPID and a calibration was performed before taking any measurement so that the 2D fluence (EPID response) delivered by each field in IMRT/VMAT plans is converted to a 2D dose distribution using a Calibration Unit (CU) for comparison. The measured dose distribution for each field from the original plan was compared with the measured dose distribution for each field from the modified plans so that the intrinsic errors, such as any mechanical errors (e.g. collimator, gantry and MLC position), can be eliminated. Moreover, the comparison was performed field by field and also composite dose with using a gamma analysis of 3% dose differences and 3 mm distance to agreement with global normalization criterion as shown in Figs. 2 and 4.

2.7. *Correlation of gamma passing rate with random errors*

In all 10 clinically approved plans, an original plan was delivered to EPID before treatment is delivered to the patient as part of patient specific QA procedures. A comparison between 2D predicted dose distribution and measured dose distribution was performed field by field and also composite dose using a gamma analysis of 3% dose differences and 3 mm distance to agreement with global normalization criterion to assess the quality of the plan. After the first treatment delivery to the patient was completed, the log files were used to reconstruct the plan for DVH recalculation. The dose difference in DVH between the original and recalculated plan was obtained and correlated with the results from EPID measurement.

3. Results

3.1. *Analysis of systematic errors based on dose volume indices*

Fig. 1 shows the average dose error in the D98%, Dmean, and D2% of the PTVs and OARs of three head and neck (Table 1) and three prostate cases (Table 2), due to the systematic errors induced in the MLC position of bank A. As expected, a positive linear relationship was observed between the MLC and dose error in DVH, due to the induced systematic errors of 0.25, 0.5, 0.75 and 1.0 mm. The average dose errors in D98%, Dmean, and D2% of the PTVs in relation to shift in the MLC are shown in Fig. 1(c) and (f), with values ranging from 2.02% mm^{-1} to 2.99% mm^{-1} for IMRT and 2.84% mm^{-1} to 3.56% mm^{-1} for VMAT in the three prostate cases, and from 4.53% mm^{-1} to 6.12% mm^{-1} for IMRT and 2.00% mm^{-1} to 2.36% mm^{-1} for VMAT in the three head and neck cases. The average dose errors in D98%, Dmean, and D2% of the OARs in relation to shift in the MLC are shown in Fig. 1(a)–(b) and Fig. 1(d)–(e), and ranged from 2.29% mm^{-1} to 4.34% mm^{-1} for IMRT and 3.24% mm^{-1} to 4.89% mm^{-1} for VMAT in the three prostate cases, and from 4.14% mm^{-1} to 8.29% mm^{-1} for IMRT and 0.42% mm^{-1} to 8.05% mm^{-1} for VMAT in the three head and neck cases.

Fig. 3 and Table 3 summarizes the impact of gantry positioning error on the average dose error in the DVH for all VMAT plans. The systematic errors in gantry position of 0.25°, 0.5°, 0.75° and 1.0° induced in all VMAT plans resulted in different outcomes, with average dose errors in the D98%, Dmean, and D2% of PTVs and OARs having either positive, negative, or near zero relationships. The average dose errors in D98%, Dmean, and D2% of the PTVs per degree shift in gantry position are shown in Fig. 3(c) and (f), and ranged from −0.11% to 0.11% deg^{-1} for the three prostate cases and −3.63% to −0.02% deg^{-1} for the three head and neck cases. The average dose errors in D98%, Dmean, and D2% of the OARs per degree shift in gantry position are shown in Fig. 3(a)–(b) and (e)–(f), and ranged from −0.13% to 0.32% deg^{-1} for the three prostate cases and −0.09% to 0.03% deg^{-1} for the three head and neck cases.

3.2. *Correlation of gamma passing rate with systematic errors*

Fig. 2(a) shows the average gamma passing rate per-field of IMRT or VMAT plans with systematic shift in MLC position. The results have shown that an average of more than 90% gamma pass rates were achieved using the 3%/3 mm criterion for all plans with systematic shift in the MLC position of up to 1 mm using either IMRT or VMAT. Similar results are shown in Fig. 2(b) for composite dose gamma analysis, except for head and neck cases using IMRT; A shift of 1 mm resulted in an average pass rates of 94.60% ± 7.

The effect of introducing systematic shift in gantry position of up to 1 degree in VMAT plans on gamma analysis is presented in Fig. 4. Per-field or composite dose gamma analysis have all shown an average of 100% pass rate for all VMAT plans with systematic shift in gantry position of up to 1 degree.

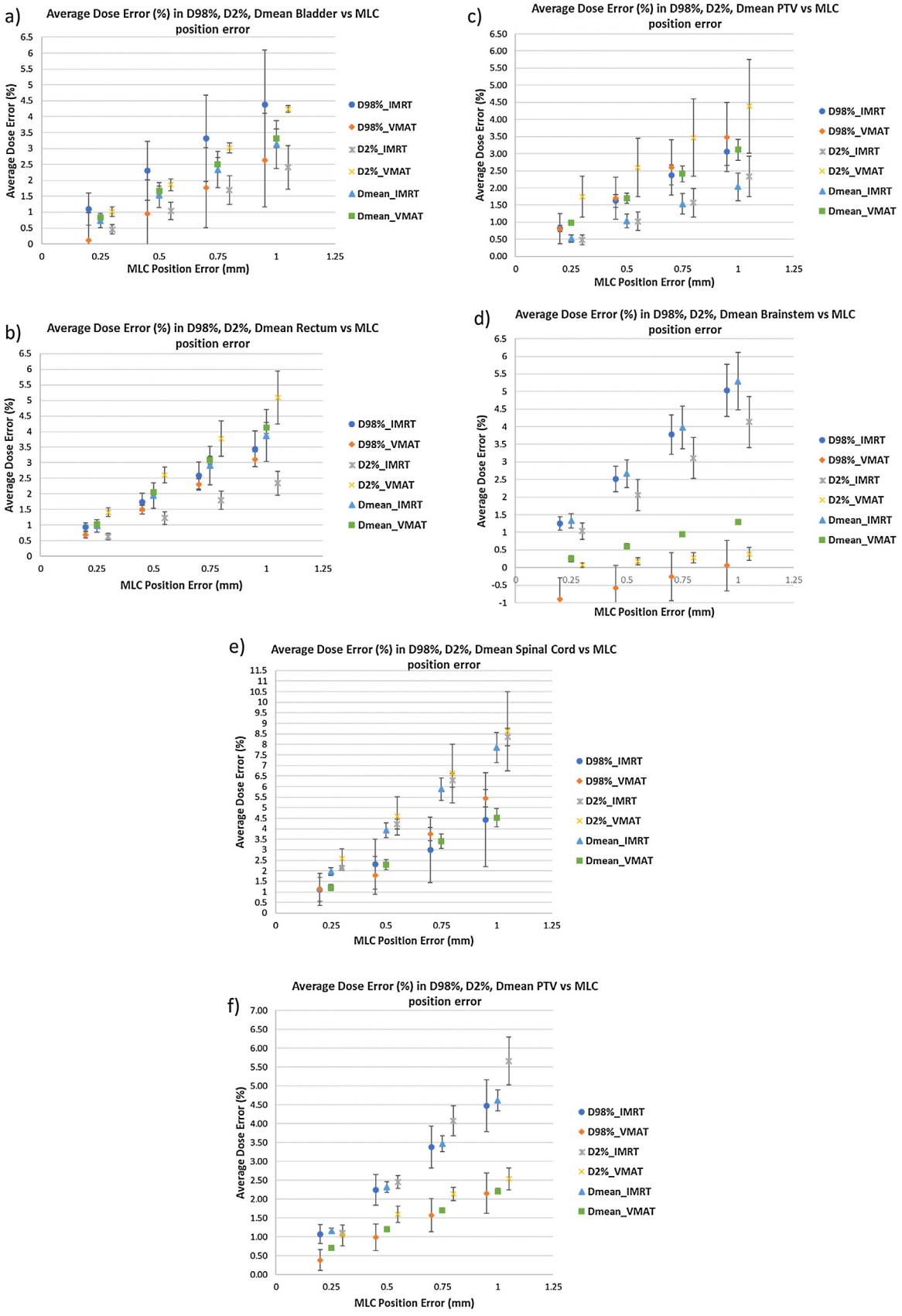

Fig. 1 – Systematic MLC positioning error vs. average dose error in D98%, Dmean, and D2% for (a) bladder; (b) rectum; and (c) PTV, of three Prostate cases, and (d) brainstem; (e) spinal Cord; and (f) PTV, in three head and neck cases. IMRT and VMAT delivery are compared.

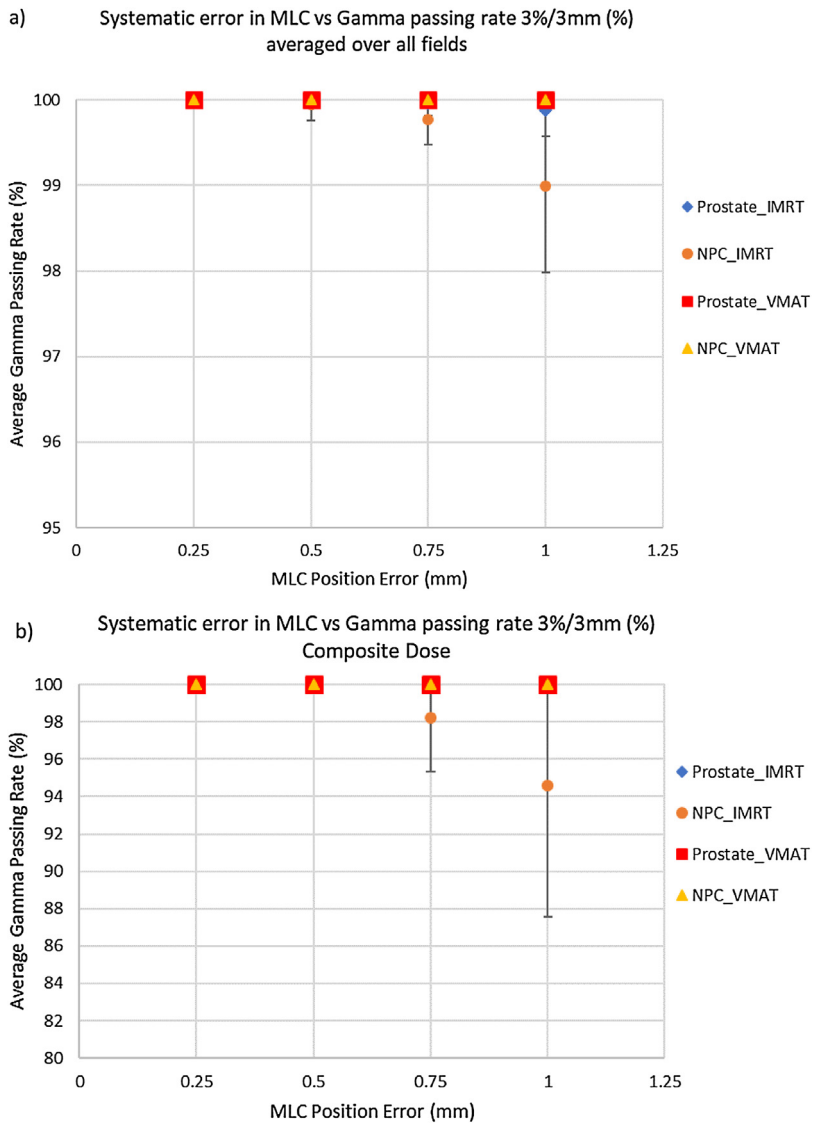

Fig. 2 – Systematic MLC positioning error vs. average gamma passing rates for three Prostate cases, and three head and neck cases (a) averaged over all fields and (b) composite dose. IMRT and VMAT delivery are compared.

3.3. *Correlation of gamma passing rate with random errors*

Fig. 5 summarizes the relationship between gamma passing rate (%) under the criteria of 3%/3 mm and the mean dose error in the D98%, Dmean, and D2% of the OARs and PTVs. Both IMRT and VMAT plans were analyzed separately due to the fact that the VMAT plans contained additional delivery parameters, such as gantry position, which contributed to the errors in dose delivery. It can also be observed from Fig. 5. that the gamma passing rate in VMAT was significantly lower than IMRT (two-tailed, $P<0.05$), ranging from 92.4% to 96.5% for VMAT vs. 96.5% to 99.4% for IMRT averaged over all fields, and 86.5% to 96.3% (VMAT) vs. 97.5% to 99.7% (IMRT) for the composite dose of all fields.

For both IMRT and VMAT plans, Pearson-R correlation tests indicated no significant correlations between gamma passing rates under the criteria of 3%/3 mm for the composite dose of all fields and the mean dose error in DVH ($r<0.3$, $P>0.05$) as shown in Fig. 5(b) and (d). A significant positive moderate correlation was found between the gamma passing rate of 3%/3 mm (%) averaged over all fields and the mean dose error in DVH of the VMAT plans ($r=0.59$, $P<0.001$). Fig. 5(c) shows that a low gamma passing rate of 92.37% indicated a mean dose error in DVH of 0.1 ± 0.07% and that a gamma passing rate of 96.47% indicated a higher mean dose error in DVH of 0.81 ± 0.33%. On the other hand, there was a significant negative correlation between 3%/3 mm gamma passing rate (%) averaged over all fields and mean dose error in IMRT plans ($r=-0.41$, $P<0.001$), and it can be observed in Fig. 5(a) that a low gamma passing rate of 96.5% indicated a mean dose error in DVH of 0.22 ± 0.42% and a high gamma passing rate of 99.43% indicated a mean dose error in DVH of 0.05 ± 0.22%.

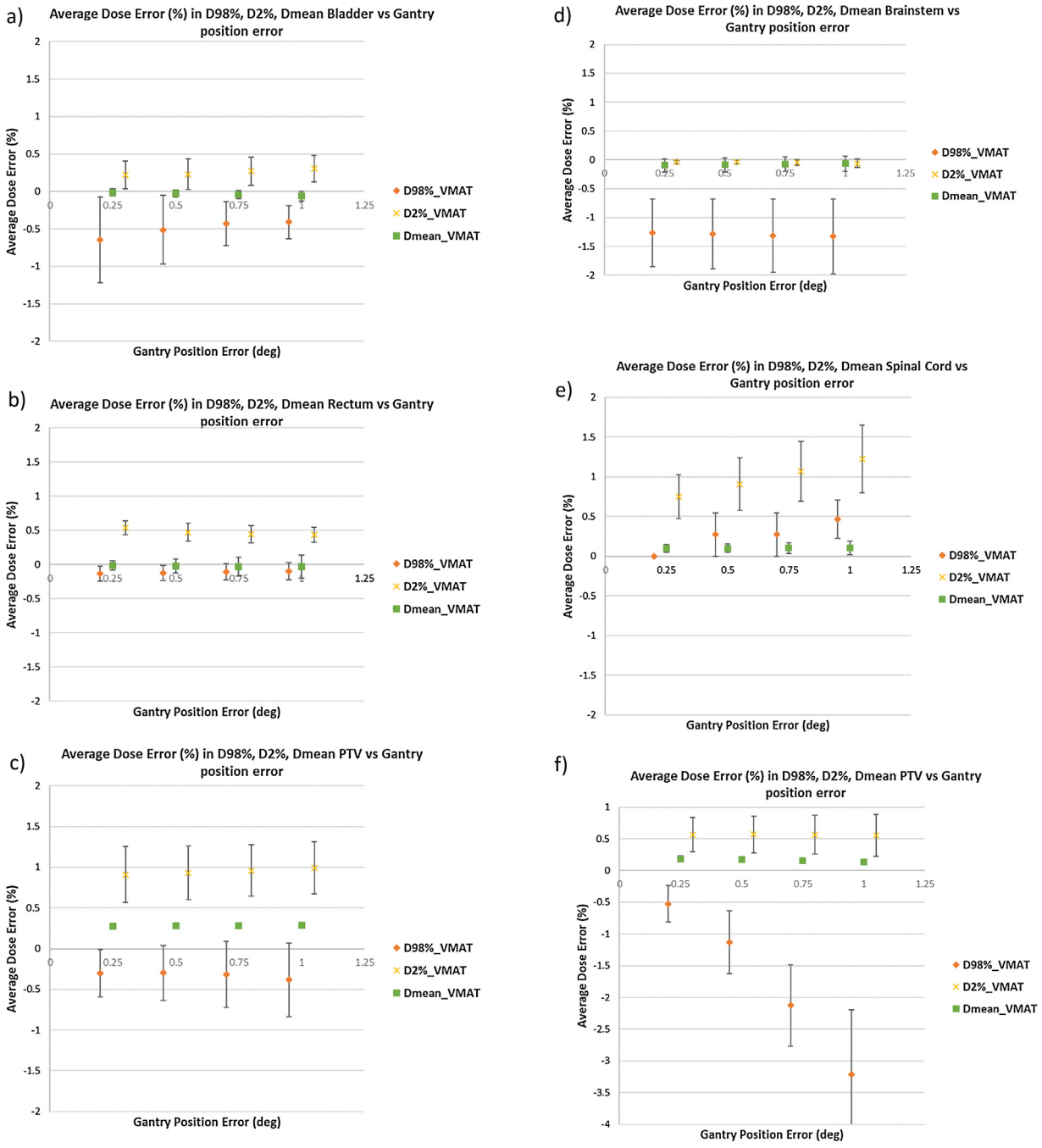

Fig. 3 – Systematic gantry positioning error vs. average dose error in the D98%, Dmean, and D2% of (a) bladder; (b) rectum; and (c) PTV, in three Prostate cases, and (d) brainstem; (e) spinal cord; and (f) PTV, in three head and neck cases (VMAT delivery).

4. Discussion

This study investigated and demonstrated the success of our in-house program, which obtains information from the trajectory log file generated by the linac to provide accurate information on the magnitude of dose delivery in OARs and PTVs. Moreover, the results obtained quantitatively by making comparisons with the DVH (original plan vs. recalculated plan) were correlated with the gamma passing rate of per-field analysis (3%/3 mm with a 90% passing rate as action levels and global normalization) and investigated.

The main advantage of using the trajectory log files is that they allow the generation of DVHs, which permit comparisons between original and recalculated plans in which the original parameters have been replaced by actual delivery parameters. This, in turn, allows the observation of errors with respect to each target volume, which would not be possible by other methods, as shown in Fig. 6. Patient dose can also be monitored daily using log files based method to generate the actual

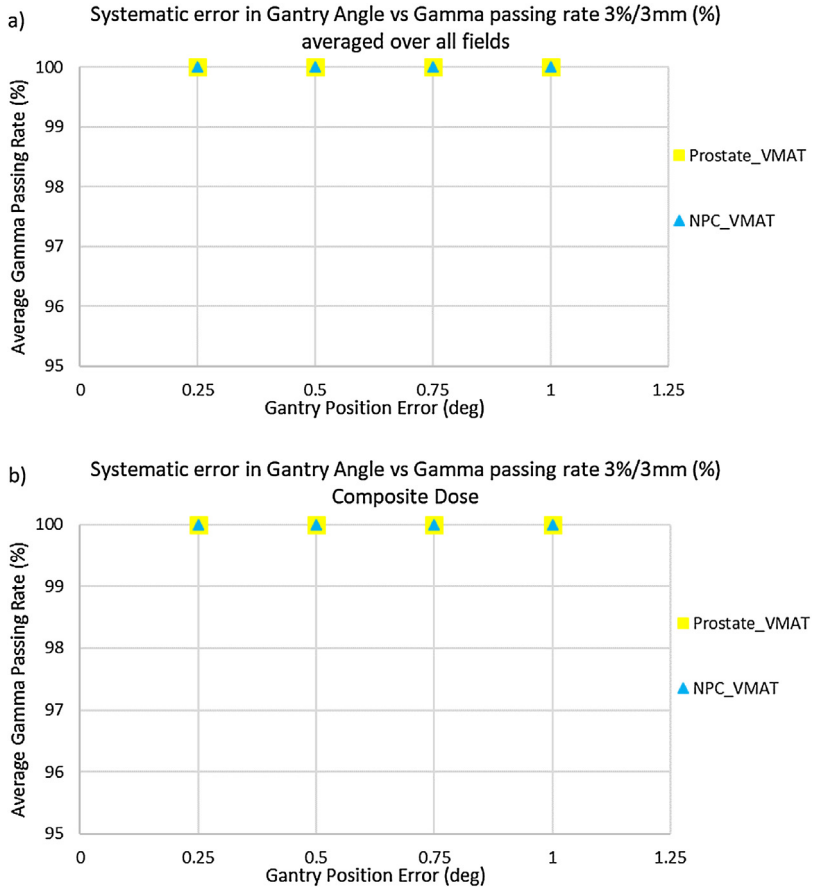

Fig. 4 – Systematic gantry positioning error vs. average gamma passing rates for three Prostate cases, and three head and neck cases (a) averaged over all fields and (b) composite dose. IMRT and VMAT delivery are compared.

DVH, and this also ensures consistency in the delivery. Moreover, if the dose error in either the OAR or PTV, does not meet the requirements, an adaptive radiotherapy approach could be used to correct the dose error in the next treatment by performing a replan.

4.1. *Systematic MLC errors in IMRT and VMAT plan*

Fig. 1 shows that the systematic MLC positioning errors introduced into the plans showed a greater impact on VMAT dose delivery than on IMRT delivery in prostate cases, with the situation being opposite for head and neck cases. Based on our results, a commonly used gamma index of 3%/3 mm for patient specific QA have shown that there is a lack of correlation between systematic MLC errors and the gamma passing rate of per-field analysis. Furthermore, the analysis is also giving some false negative results indicating a false sense of security that the plan has minimal patient dose error as shown in Fig. 2. However, in Fig. 2(b) when evaluating the results for composite dose analysis; head and neck cases using IMRT technique with a shift of 1 mm in MLC position have shown to fail (<90% gamma passing rate) the 3%/3 mm criterion with an average of 94.60% ± 7.0, but this does not provide any information on the location and magnitude of errors. This type of analysis can only be obtained with the use of the trajectory log file method and not by portal dosimetry as shown in Figs. 2 and 4. Therefore, our study has proven the sensitivity of trajectory log files to detect systematic MLC errors in complex IMRT and VMAT plans.

4.2. *Systematic gantry position errors in VMAT plan*

For all VMAT plans with a systematic shift in gantry position of up to 1° (clockwise), the results presented in Fig. 3 show that the dosimetry errors are small and insignificant. Although the dosimetric errors caused by the systematic errors in gantry position were small, the inconsistencies are due to the fact that any deviation from the initial planned gantry position may cause the field shaped by the MLC in each control point to over or under shield both OARs and PTVs from dose delivery. In Fig. 4, regardless of per-field planar dose analysis or composite dose analysis performed using a 3%/3 mm criterion, the results have clearly shown that no correlation can be established between gamma passing rate and gantry positioning error. The insensitivity of EPID based QA towards systematic shift in the gantry error of VMAT plans are due to the fact that during delivery, the portal imager is always perpendicular to the beam. Moreover, fluences delivered by VMAT with systematic shift in the gantry angle at every control point are superimposed to produce a 2D dose distribution and, therefore, unable to investigate the impact of gantry positioning error using gamma analysis.[22]

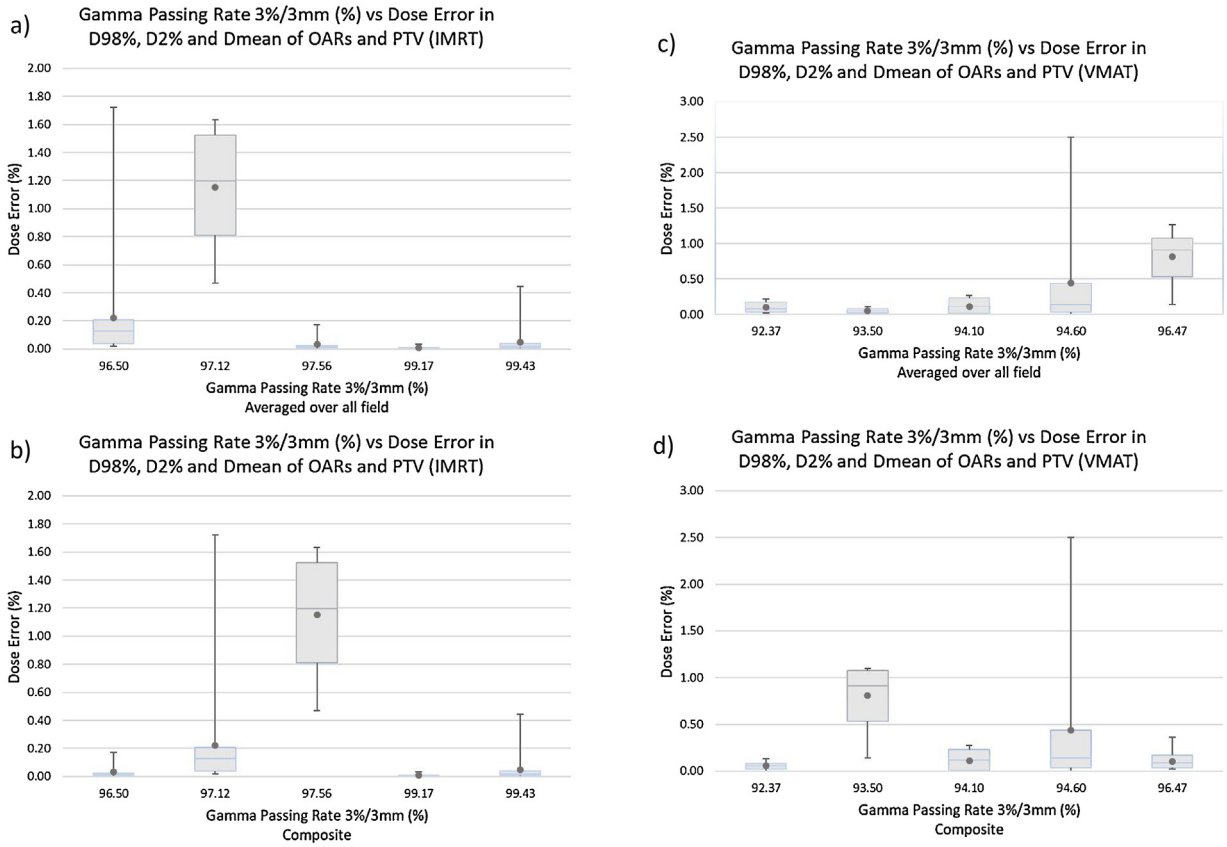

Fig. 5 – Dose error in the D98%, Dmean and D2% for OARs and PTVs calculated with the IMRT and VMAT techniques and analyzed using (a), (c), the gamma passing rate of 3%/3 mm (%) averaged over all fields and (b), (d), the composite dose of all fields.

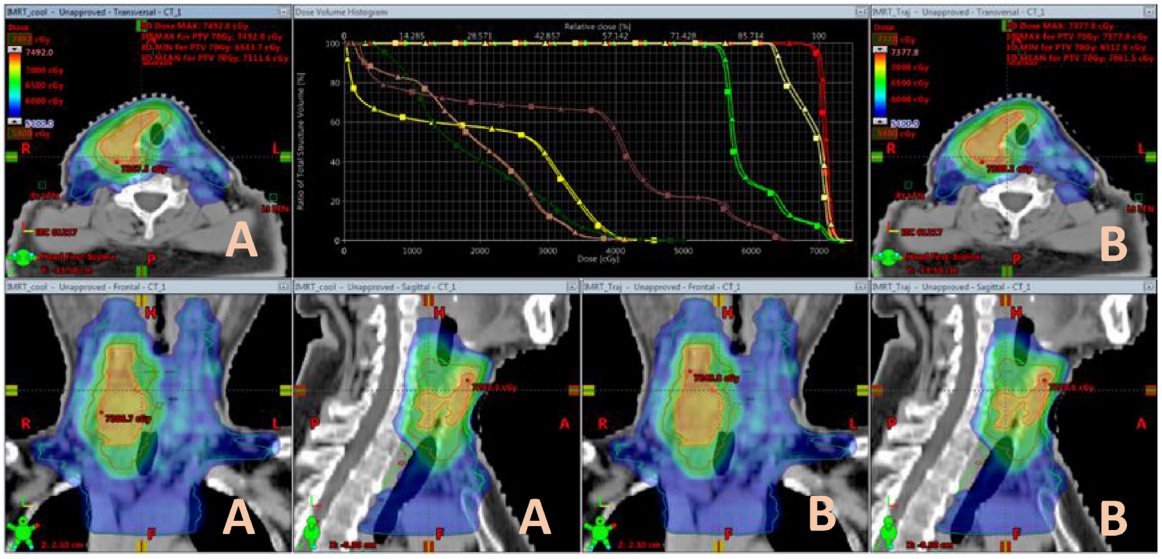

Fig. 6 – A comparison between original plan (A) and recalculated plan (B) with the actual delivery parameters used in the plan evaluation. Comparison of the DVHs shows the differences in dose distribution in each target volume.

4.3. *Random errors in 10 clinically treated plans*

Based on our results shown in Fig. 5, it can be concluded that a single pass or fail for per-field analysis or composite dose comparisons under the criteria of a 90% passing rate applied as action level with 3%/3 mm gamma analysis, could not explain or predict the location and magnitude of the dose error for OARs and PTVs in all 10 clinically approved treatment plans, regardless of whether a plan was for IMRT or VMAT. Additionally, the composite dose comparisons shown in Fig. 5(b)

and (d) between 2D predicted and measured dose distributions poorly predicted the overall accuracy of the patient dose. A comparison of the 2D dose distributions per-field using gamma analysis in all 5 clinically approved IMRT plans shown in Fig. 5(a) does at least indicate that a higher gamma passing rate will result in a lower mean dose error in OARs and PTV, but weak correlation between them was observed which is in agreement with the literature.[7,8,23]

In VMAT deliveries, the added complexity due to the additional parameter of gantry position may have contributed to a larger range of dose error in DVH and a lower passing rate in the gamma analysis in comparison to IMRT, with this being the case in all ten clinical cases as shown in Fig. 5, with the average dose error ranging from −1.43% to 2.50% for VMAT vs. −1.72% to 0.44% for IMRT. In agreement with the literature,[7] a positive correlation between gamma passing rates and mean dose error in DVH shown in Fig. 5(c) indicates that DVH errors were larger for higher gamma passing rates in VMAT deliveries. Furthermore, the composite dose comparison of all fields does not indicate a correlation between gamma passing rates and mean dose error in DVH in either IMRT or VMAT deliveries as shown in Fig. 5(b) and (d).

Nevertheless, patient specific QA performed by EPID is still important and should not be neglected, as it is crucial for the detection of errors, especially in busy centers with pressure on machine time[12] because errors, such as communication between the ARIA and Eclipse system, absolute dose error and starting jaw position error, especially for a linac capable of jaw tracking in IMRT plans, can delay the starting time of a patient's treatment. However, gamma analysis will not be able to give exact information on the absolute dose error with respect to the location of each target volume. Therefore, our trajectory log file based method has demonstrated that it has the sensitivity to detect the absolute dose error between an original plan and a recalculated plan. The disadvantages of DVH based QA is that it is unable to assess errors such as patient set up, changes in the linac daily output and also MLC calibration errors (e.g. transmission factor, tongue and groove effect).

Osewski et al.[10] and Calvo-Ortega et al.[9] both presented a similar reconstruction method based on dynalog files to recalculate the actual dose distribution in TPS, but in contrast to our work, they did not perform a correlation between the dose differences found in DVH to gamma index passing rate in order to evaluate the sensitivity of gamma index. Furthermore, new generation of linac comes with a trajectory log file in a binary format which is more difficult to extract information from when compared with the dynalog file.

From these results, we are able to study the clinical impact on patient dose of MLC and gantry positioning errors. Dose rate, however, is not a part of this study, as it has been shown[12,21] to have very little impact on the dose differences. It is important to emphasize that the more commonly used default settings for gamma analysis has a limitation with 3%/3 mm criteria, hence more stringent gamma criteria, such as 2%/2 mm or less, should be further investigated. It is also important to note that this study is not meant to imply that the DVH based QA developed by us is capable of replacing any patient specific QA performed using an EPID or any other phantom based system, but that it could be benefited when used in conjunction with them, to balance out the disadvantages of both systems.

5. Conclusion

This study has shown the sensitivity of trajectory log files to detect the impact of systematic MLC errors and random errors in dose delivery for complex IMRT and VMAT plans. There is a strong positive linear relationship between MLC positioning and dose error in all OARs and PTVs in both IMRT and VMAT plans. However, gantry positioning errors exhibit little impact on dose error in all OARs and PTVs. By correlating the gamma passing rates with mean dose error in DVH calculated using the trajectory log files, our results confirm that 3%/3 mm gamma index criteria are insensitive to detect any systematic error in MLC and gantry position.

Conflict of interest

None declared.

Financial disclosure

None declared.

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