

Impact of dose rate on accuracy of intensity modulated radiation therapy plan delivery using the pretreatment portal dosimetry quality assurance and setting up the workflow at hospital levels

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ABSTRACT

The aim of this study was to examine the impact of dose rate on accuracy of intensity modulated radiation therapy (IMRT) plan delivery by comparing the gamma agreement between the calculated and measured portal doses by pretreatment quality assurance (QA) using electronic portal imaging device dosimetry and creating a workflow for the pretreatment IMRT QA at hospital levels. As the improvement in gamma agreement leads to increase in the quality of IMRT treatment delivery, gamma evaluation was carried out for the calculated and the measured portal images for the criteria of 3% dose difference and 3 mm distance-to-agreement (DTA). Three gamma parameters: Maximum gamma, average gamma, and percentage of the field area with a gamma value > 1.0 were analyzed. Three gamma index parameters were evaluated for 40 IMRT plans (315 IMRT fields) which were calculated for 400 monitor units (MU)/min dose rate and maximum multileaf collimator (MLC) speed of 2.5 cm/s. Gamma parameters for all 315 fields are within acceptable limits set at our center. Further, to improve the gamma results, we set an action level for this study using the mean and standard deviation (SD) values from the 315 fields studied. Forty out of 315 IMRT fields showed low gamma agreement (gamma parameters > 2 SD as per action level of the study). The parameters were recalculated and reanalyzed for the dose rates of 300, 400 and 500 MU/min. Lowering the dose rate helped in getting an enhanced gamma agreement between the calculated and measured portal doses of complicated fields. This may be attributed to the less complex motion of MLC over time and the MU of the field/segment. An IMRT QA work flow was prepared which will help in improving the quality of IMRT delivery.

Key words: Dose rate, electronic portal imaging device, gamma evaluation, intensity modulated radiation therapy, portal dosimetry

Introduction

Intensity modulated radiation therapy (IMRT) allows for the radiation dose to conform more precisely to the three-dimensional shape of the tumor by

controlling (modulating) the intensity of the radiation beam.^[1] The non-uniform radiation intensity of an individual IMRT beam is optimized using inverse planning optimization process, and it is delivered via multileaf collimator (MLC) by either dynamic mode (DMLC) or step and shoot mode (SMLC). In DMLC, the leaves move continuously during the beam on time while in SMLC delivery the radiation is turned off while the aperture shapes change.^[2,3] In IMRT optimizations, the radiation

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intensity map of the beam is defined by optimizing each bixel (beam pixel) of the beam. The IMRT optimization modifies the beam intensity maps in each iteration and calculates the dose after each modification. After successful optimization, the intensity, or fluence maps have to be converted, in a case of MLC delivery technique, to a series of MLC shapes or movements. This is usually executed by a leaf sequencing algorithm (leaf motion calculator [LMC]), which is a separate algorithm for the allowed and possible MLC shapes. Optimal fluence does not consider the mechanical components of the linear accelerator, limitations of MLC, and beam delivery.^[4] Leaf motions calculated in the LMC considers the limitations of the linear accelerator and MLC (MLC leaf transmission, dosimetric leaf gap, MLC interleaf leakage, maximum MLC leaf speed, energy of the beam, and maximum dose rate of the beam).^[5,6] LMC calculates the actual fluence that approximates the desired optimal fluence, and it is used for the final dose calculation in the treatment planning system (TPS). Verification of actual fluence of an IMRT beam is necessary to assure the correct dose delivery to the patient. In view of these complex parameters involved in IMRT delivery, we have studied the dose rate effect on the pretreatment quality assurance (QA) of IMRT plans using the portal dose prediction method, and analyzed results are presented. Different methods such as film dosimetry, point dose measurements using ion chambers, and planar dose distribution measurements using detector arrays (Electronic Portal Imaging Device [EPID], Imatrixx, Map Check, etc.) are used for QA of IMRT plans.^[7-9]

Materials and Methods

Linear accelerator and electronic portal imaging device

All IMRT plans analyzed in this study were planned for 6 MV photon beams of Clinac iX Linear Accelerator (Varian Medical Systems, Palo Alto, CA, USA), which was equipped with 120 leaf-millennium MLC with 5 mm and 1 cm resolution at isocenter. Maximum leaf speed was 2.5 cm/s, minimum leaf gap between opposite banks was 0.5 mm. The Clinac iX Linear Accelerator was capable of delivering 6 MV photons in six different dose rate (100, 200, 300, 400, 500, and 600 monitor units [MU]/min).

All EPID images analyzed in this study were acquired with an amorphous silicon (aSi) indirect-detection EPID (Varian Medical Systems, Palo Alto, CA, USA) mounted on the Exact arm of the Varian Clinac iX Linear Accelerator. The exact arm is a robotic arm, attached directly to a linear accelerator that is remotely positioned with high accuracy, and reproducibility. The portal vision as 1000 flat-panel EPID has a 40×30 cm² detecting surface area with a matrix of 1024×768 pixels (0.392 mm pixel pitch). All IMRT EPID images were acquired at a target to detector distance of 100 cm with no additional buildup. ARIA integration

system (version 8.8, Varian Medical Systems, Palo Alto, CA, USA), and the portal dosimetry system (Varian Medical Systems, Palo Alto, CA, USA) for portal dose image prediction calculations and data analysis were used in this study. aSi-EPID and its usefulness for IMRT pretreatment dosimetric purposes have been quite extensively discussed in several studies. The linearity of dose response, field size dependence, reproducibility overdose rate, gravity effect, dose rate dependence, and independence on beam energy of the aSi-EPID have been proven by several studies.^[10-12] To perform QA for IMRT fields using EPID, one needs to configure it for absolute dose measurements. In our clinic, the EPID was calibrated according to the vendor's specification at the time of commissioning of the linear accelerator and every quarter thereafter. One must perform the calibration procedure for energy and dose rate combination that will be used for IMRT and IMRT QA.^[13]

Portal dosimetry quality assurance procedure

The verification plan was created by superimposing the patient treatment fields onto the portal imager's geometry at the designated target to imager distance (100 cm TID) using the eclipse TPS. Portal dose image for each field was calculated using the planned field size, DMLC sequence, dose rate, and number of MU same as the treatment field, and by resetting the gantry, collimator, and couch angles to 0°. Measurements are carried at 0° Gantry angle to maintain the positional accuracy of EPID detector. For some instances in which a dimension of the treatment field exceeded the active area of the portal imager, the collimator is rotated by 90° to fit the entire field within the imager's active area.

The plan which was used to create the portal image was executed at the linear accelerator and the portal image was acquired at 100 cm source-to-detector distance using the EPID. Later, gamma evaluation was performed between the acquired EPID images with portal dose prediction image in the portal dosimetry workspace of the ARIA integration system.

Portal dosimetry gamma analysis

In gamma evaluation, termed gamma (γ) was developed to take both dose and spatial difference into account to quantitatively compare dose distributions, either measured or calculated. The γ quantity degenerates to the dose-difference and distance-to-agreement (DTA) tests in shallow and very steep dose gradient regions, respectively. The gamma evaluation was carried out between the portal dose prediction image and the acquired portal dose image, and the three scalar parameters of gamma index (maximum gamma [γ_{\max}], average gamma [γ_{avg}], and percentage of the field area with a gamma value >1.0 [$\gamma_{\%} >1$]) was evaluated for the criteria of 3% dose to 3 mm distance. All three variables of gamma lower values indicated better agreement between the measured dose and the calculated predicted portal dose image. Gamma index was calculated

in the surface area equal to the rectangular treatment field that extended by 1.0 cm around treatment field sizes. This area covered part of portal detectors covering the treatment field, so it showed how the dose was deposited within the treatment field. The viewer options in portal dosimetry workspace allow the user to define the tolerance values of gamma index and apply different display settings in the presentation of gamma maps. The portal dosimetry workspace will allow us to define the region of interest of evaluation and the dose and DTA criteria.

Study design

In this study, 40 IMRT treatment plans, consisting of 315 IMRT fields which were calculated at 400 MU/min dose rate (clinically used dose rate at our center) and maximum MLC speed of 2.5 cm/s and treated at our center from July 2014 to September 2014 were analyzed. For all IMRT plans, pretreatment QA using EPID was performed on the same day or 1-day prior to the actual treatment delivery. From our ARIA Integrating System database, we noted γ_{\max} , γ_{avg} , and $\gamma_{\%} > 1$ values for 315 treatment fields and calculated the mean values for each parameter and their associated standard deviations (SD). Gamma parameters for all 315 fields were within acceptable limits set at our center. Further to improve the gamma results, we set an action level for this study using the mean and SD values from these 315 fields.

Action level

We set action level for this study using the gamma parameters calculated here.

- The values for γ_{\max} , γ_{avg} , and $\gamma_{\%} > 1$ for all fields in an IMRT plan must be within 2 SD of the study mean value
- If the gamma index value is found to be more than 2 SD from the mean, then the measurement has to be repeated with different dose rate (300 and 500 MU/min) and analyze the impact of dose rate for those fields.

Method to improve gamma agreement between the calculated and measured portal doses

In theory, lower the gamma index values are, better is the agreement between the calculated and measured portal doses and that it quantifies the accuracy of IMRT delivery. We should look for the lower gamma index values in QA measurements. To improve the gamma agreement between the measured and calculated portal doses, one needs to change the MLC parameters and beam constraints in the LMC algorithm. Modifying the values of the MLC constraints such as MLC leakage, MLC inter and intra leaf transmission, dynamic leaf gap is generally not advisable. Because these MLC parameters are not variables, their values were measured for the particular MLC leaves. Some studies show that the change in leaf velocity (maximum MLC speed) and dose rate of the beam are shown better agreement between the measured and calculated dose planes.^[14,15] Modifying the maximum

MLC speed is also not advisable because it is an intrinsic machine parameter, and changing maximum MLC speed would affect the other ongoing IMRT plans. Changing the dose rate is easy and further, it will not affect the normal work flow. Hence, the leaf-motions were re-calculated using LMC for the fields, which had shown more gamma deviations (fields that had values for one or more gamma parameters, more than 2 SDs from the study mean value) at lower dose rate (300 MU/min) and higher dose rate (500 MU/min). The IMRT QA was repeated for each new field, and the results were documented. Further, we compared the point dose measurements for the same IMRT fields for the modified dose rate.

Point dose measurements

SP34 solid water phantom (iba Dosimetry, GmbH, Germany) was used to measure the point dose at isocenter with an FC65G Farmer type ion chamber (iba Dosimetry, GmbH, Germany). The dimension of the SP34 phantom is 300 mm × 300 mm × 200 mm (20 numbers of 10 mm thickness SP34 water slabs) and is made of the RW3 material. The phantom plan was created at Eclipse TPS by superimposing the patient IMRT fields into a phantom, and the gantry, collimator, and couch angles were made to 0°. Phantom plans were calculated for 90 cm SSD and 10 cm depth for the calculation grid of 2.5 mm using AAA algorithm. Point dose measurements were carried out for three different dose rates (300, 400 and 500 MU/min) at the linear accelerator by the above-mentioned setup geometry. The percentage differences were calculated by the following formula:

$$\text{Percentage deviation} = \left(\frac{[\text{Measured Dose}_{300 \text{ or } 500} - \text{Measured Dose}_{400}]}{\text{Measured Dose}_{400}} \right) \times 100$$

Meas Dose₃₀₀ - Measured dose at isocenter for the 300 dose rate

Meas Dose₄₀₀ - Measured dose at isocenter for the 400 dose rate

Meas Dose₅₀₀ - Measured dose at isocenter for the 500 dose rate

Results and Discussion

Figure 1 shows a scatter plot of maximum gamma (γ_{\max}), average gamma (γ_{avg}), and percentage of the field area with a gamma value > 1.0 ($\gamma_{\%} > 1$) values for each of the 315 treatment fields evaluated in our study for the criteria of 3% dose difference and 3 mm DTA. The scale of the average gamma is approximately 10 times lower than that of maximum gamma and area gamma > 1 values. Thus, we plotted the maximum gamma and area gamma > 1 values using the primary ordinate axis and the average gamma values using secondary ordinate axis. Table 1 presents the values of mean and their associated SDs for each gamma

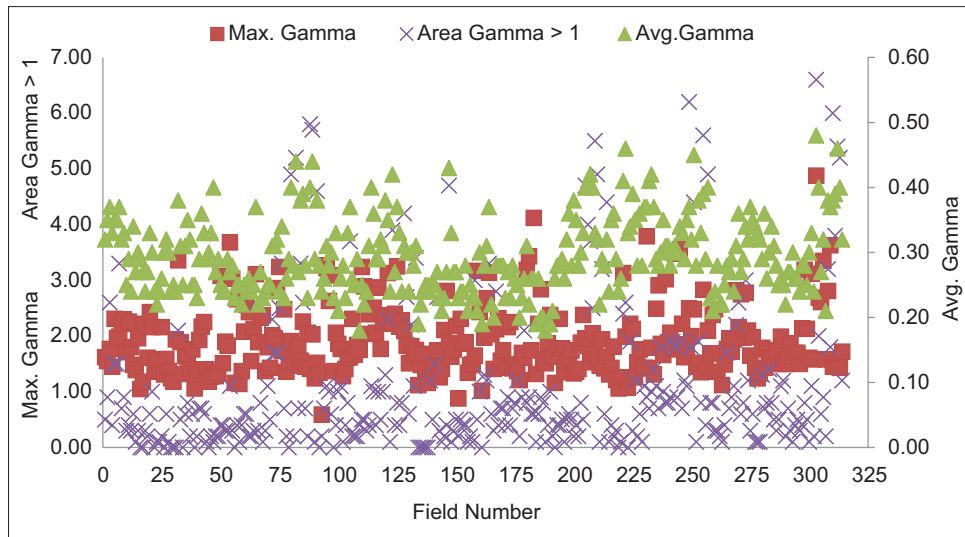


Figure 1: Scatter plot of maximum gamma, average gamma, and area gamma >1 for each field evaluated in this study

parameter for all the fields. For all the 315 fields, the gamma evaluated by the portal dosimetry software for the criteria of 3% dose difference and 3 mm DTA were within the tolerance limits ($\gamma_{max} = 4.0$, $\gamma_{avg} = 0.5$ and $\gamma_{% >1} = 7%$) set at our center. Our data are in good agreement with data published by several studies using the EPID dosimetry analysis.^[15,16]

The effect of dose rate on gamma agreement between the calculated and measured portal dose

From the mean and SDs of the 315 fields studied, 275 (87.3%) had one or more values <2 SDs from the mean and 40 fields (12.7%) had one or more values greater than 2 SDs from the mean. As per the action level defined for this study, we recalculated the leaf motions using LMC for the fields at lower dose rate (300 MU/min) and higher dose rate (500 MU/min) for the 40 fields which had showed gamma deviation more than 2SDs from the mean. We repeated the portal dosimetry QA procedure for each new field, and the results were documented. Figures 2-4 show the comparison column chart for the three gamma parameters at three different dose rates, respectively. Table 2 provides the mean and SD values for γ_{max} , γ_{avg} and $\gamma_{% >1}$ for fields that were re-calculated with lower dose rate (300 MU/min) and higher dose rate (500 MU/min).

The gamma agreement in 31 of the 40 fields that were re-planned with lower dose rate (300 MU/min) improved. In nine fields, it was found/we found that lowering the dose rate actually resulted in a worse agreement between the calculated and measured portal dose than that found with the initial dose rate (400 MU/min). Re-calculated fields at the higher dose rate (500 MU/min) showed the increasing gamma values for 28 fields and resulted in a worse gamma agreement. In 12 fields, the increased dose rate (500 MU/min) showed lesser or equal gamma values of the fields calculated with 400 MU/min dose rate.

Table 1: Mean and SDs of gamma parameters for 315 fields

	Gamma maximum	Gamma average	Area gamma >1
Mean	1.92	0.30	1.08
SD	0.64	0.08	1.35
Mean±SD	2.56	0.38	2.43
Mean±2 SD	3.20	0.45	3.77
Mean±3 SD	3.84	0.55	5.12
	Number of fields (%)		
Mean±2 SD	16 (5.0)	4 (1.3)	22 (7)
Mean±3 SD	2 (0.6)	1 (0.003)	10 (3.2)

SDs: Standard deviations

The results show that re-calculating the fields at lower dose rate (300 MU/min) decreased gamma values compared to the increased dose rate (500 MU/min). Re-calculating the fields at lower dose rate (300 MU/min) was an effective strategy for decreasing gamma values, thereby improving the agreement between the measured portal dose and the calculated portal dose. Using this method, we were able to improve the gamma agreement for 77.5% (31 fields) of fields that were recalculated. Our results suggest that lowering the dose rate can be an effective strategy for improving gamma agreement between the calculated and measured portal doses. This improvement can be linked to an increase in the time allotted for the delivery of each field segment. It concludes that this may be attributed to less complexity in the MLC motion with lower dose rate and MU specified for particular fields. Lowering the dose rate decreases the number of control points per minute that helps the smoother MLC delivery over time. Increasing the dose rate increases the number of control points per min and increases the complexity of the MLC delivery that increases the gamma index values. The higher dose rates may not optimally synchronize with the MLC motion and thereby affect the accuracy of the dose delivery. Further, we

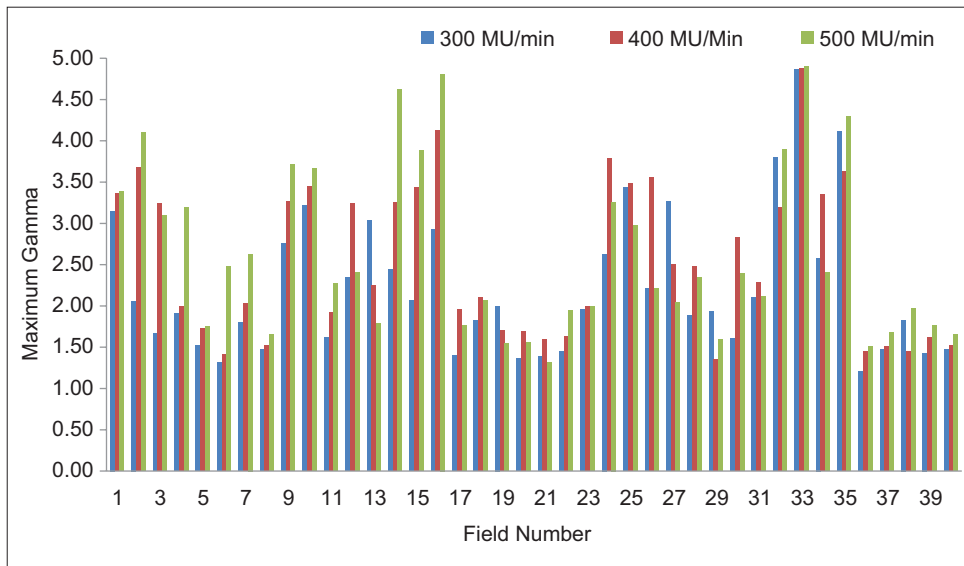


Figure 2: Comparison column chart - maximum gamma for 40 fields for three different dose rates

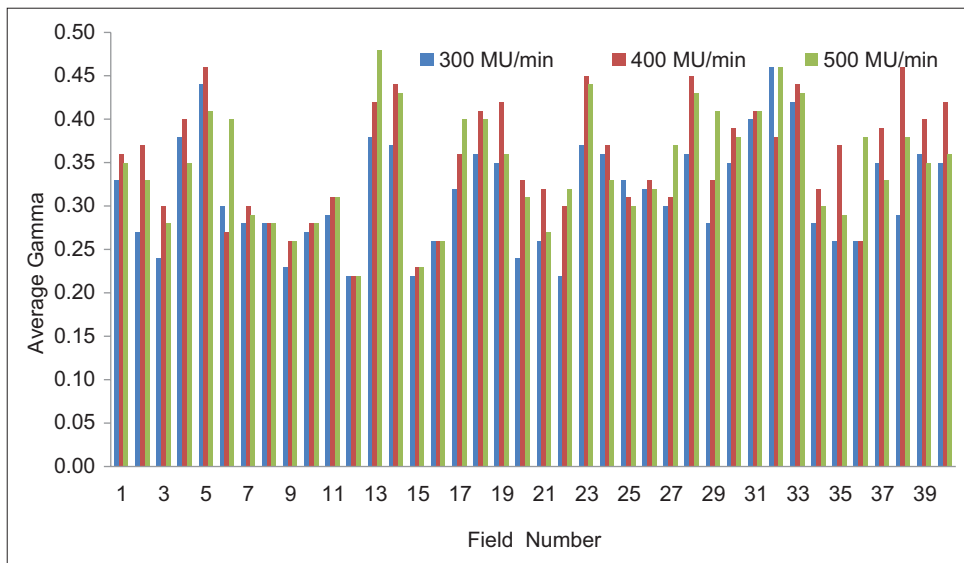


Figure 3: Comparison column chart - average gamma for 40 fields for three different dose rates

measured the point dose at isocenter for the three different dose rate IMRT fields to find the deviation in the absolute dose.

Point dose measurements

Absolute dose measurements were carried out using SP34 water phantom with FC65G ion chamber. Verification plans were created and calculated in TPS. Absolute dose measurements for three different dose rates (300, 400, and 500 MU/min) were measured for 40 fields which showed poorest gamma agreement in portal dosimetry analysis and the percentage deviation for point dose were calculated. The results show that <1% mean deviation between the measured and calculated absolute doses, which is acceptable. However, further study is needed to use the same dose rate for the entire plan and assess the dose distribution.

Intensity modulated radiation therapy quality assurance workflow

We created a workflow (given below) for the IMRT treatments in our clinic based on the findings from this study.

- Perform the pretreatment IMRT QA using portal dosimetry with 400 MU/min dose rate (default dose rate) for the approved treatment plan
- Analyze the gamma parameters and look for their acceptable limits set in the center (modified tolerance limit from the previous tolerance limits set at our center: $\gamma_{max} = 3.0, \gamma_{avg} = 0.4$ and $\gamma_{%} > 1 = 5\%$)
- If the plan fails to fall within tolerance limits, IMRT QA should be repeated using the strategy of lowering the dose rate (300 MU/min) (Leaf calculations and dose calculations)

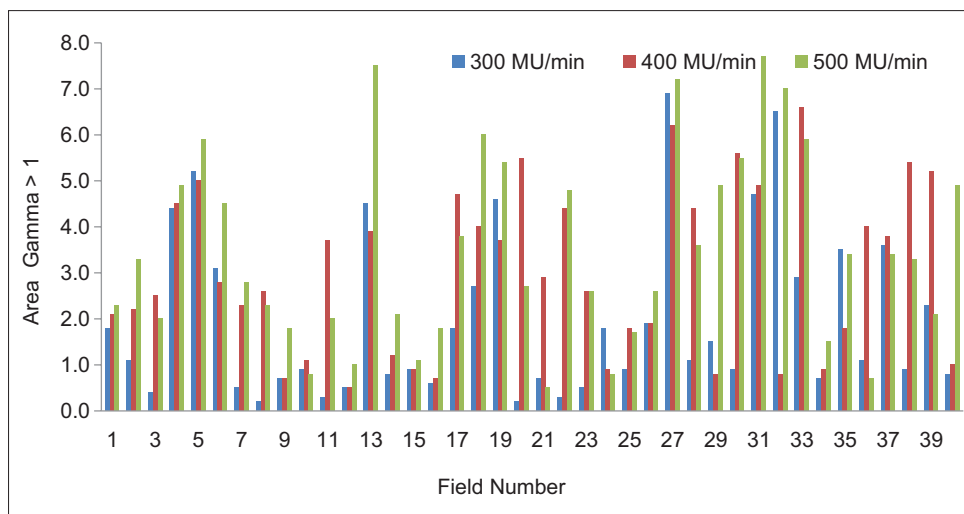


Figure 4: Comparison column chart - area gamma >1 for 40 fields for three different dose rates

Table 2: Mean of gamma parameters after the re-calculation of different dose rates

	Maximum gamma	Average gamma	Area gamma >1
315 fields (400 MU/min)	1.92	0.30	1.08
40 fields (400 MU/min) before LMC re-calculation	2.59	0.35	3.06
40 fields (300 MU/min) after LMC re-calculation	2.26	0.31	2.00
40 fields (500 MU/min) after LMC re-calculation	2.67	0.35	3.42
Number of fields (%)			
300 MU/min (lesser gamma values than 400 MU/min)	33 (82.5)	38 (95.0)	32 (80.0)
300 MU/min (higher gamma values than 400 MU/min)	7 (17.5)	2 (5.0)	8 (20.0)
500 MU/min (lesser gamma values than 400 MU/min)	21 (52.5)	32 (80)	15 (37.5)
500 MU/min (lesser gamma values than 400 MU/min)	19 (47.5)	8 (20.0)	25 (62.5)

LMC: Leaf motion calculator, MU: Monitor units

should be recalculated for the new lower dose rate in TPS

- If the IMRT QA passes for lower dose rate, re-evaluate the plan for dose coverage, and if satisfactory, approve the plan for treatment
- If the strategy of lowering the dose rate fails, an entirely new treatment plan should be developed.

Conclusion

Portal dosimetry provides a tool for routine pretreatment QA of IMRT treatments that is potentially and significantly faster and more convenient. This study analyzed the impact of dose rate in the dynamic IMRT pretreatment verification QA fields using portal dosimetry. Based on the data it can be concluded that 400 MU/min dose rate is optimum and

lowering the dose rate helps to get an enhanced gamma agreement between the calculated and measured portal doses of complicated fields. This may be attributed to the less complex motion of MLC over time and the MU of the field/segment. The improvement in gamma agreement leads to increase in the quality of IMRT treatment delivery. An IMRT QA workflow was created, which will help in improving the quality of IMRT delivery.

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Conflicts of interest

There are no conflicts of interest.

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