Original Article

The Impact of Dose Rate on the Accuracy of Step-and-Shoot Intensity-modulated Radiation Therapy Quality Assurance Using Varian 2300CD

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Abstract

Introduction: Intensity-modulated radiation therapy (IMRT) delivery using "step-and-shoot" technique on Varian C-Series linear accelerator (linac) is influenced by the communication frequency between the multileaf collimator and linac controllers. Hence, the dose delivery accuracy is affected by the dose rate. **Aim:** Our aim was to quantify the impact of using two dose rates on plan quality assurance (QA). **Materials and Methods:** Twenty IMRT patients were selected for this study. The plan QA was measured at two different dose rates. A gamma analysis was performed, and the degree of plan modulation on the QA pass rate was also evaluated in terms of average monitor unit per segment (MU/segment) and the total number of segments. **Results:** The mean percentage gamma pass rate of 94.9% and 93.5% for 300 MU/min and 600 MU/min dose rate, respectively, was observed. There was a significant ($P = 0.001$) decrease in percentage gamma pass rate when the dose rate was increased from 300 MU/min to 600 MU/min. There was a weak, but significant association between the percentage pass rate at both dose rate and total number of segments. The total number of MU was significantly correlated to the total number of segments ($r = 0.59$). We found a positive correlation between the percentage pass rate and mean MU/segment, $r = 0.52$ and $r = 0.57$ for 300 MU/min and 600 MU/min, respectively. **Conclusion:** IMRT delivery using step-and-shoot technique on Varian 2300CD is impacted by the dose rate and the total amount of segments.

Keywords: Dose rate, intensity-modulated radiation therapy, quality assurance, radiation therapy

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Introduction

Intensity-modulated radiation therapy (IMRT) has become the standard of care for the management of most cancers.[1-3] The success of IMRT has been due partly to the introduction of multileaf collimators (MLCs) that are used to modulate the intensity of the radiation beam to achieve a nonuniform dose distribution that is conformal to the target.[4,5] This modulation using MLC can be achieved using two techniques, namely, the sliding window (dynamic MLC [DMLC]) and the segmented (or step and shoot) (segmental MLC [SMLC]). For DMLC, the radiation is delivered by varying the velocity of the individual MLC leaves while the treatment beam is on.[6] The SMLC technique consists of a number of static subfields shaped by the MLC called segments.[4,5] In this approach, the radiation beam is interrupted while the MLC moves (step) to a predetermined location (segment) at a particular gantry angle and radiation is delivered (shoot) while the MLCs are stationary. After a segment is delivered, the beam is turned off and the MLCs move into place for the next segment.[7] Beam intensity modulation increases with the total number of beam segments, resulting in a smaller number of monitor units per segment (MU/segment).[8] It is evident that a highly precise mechanical synchronization of the MLC with the linear accelerator (linac) beam delivery system is paramount for the accurate and safe delivery of IMRT.

SMLC implementation on Varian linac C-series models (Varian Medical Systems Inc., Palo Alto, CA, USA) is affected by the design of the MLC controller and its communication with

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the linac controller.[7,9] This is because there are two types of beam dose control: total beam and segmented beam. The total beam is monitored and controlled by ionization chambers within the head of the accelerator. The segment doses and leaf coordinates are only controlled by the MLC-controller timing pulses. Hence, in SMLC, after the MLC leaves reach their predetermined positions for a particular segment, radiation is initiated by the "total beam control." During this "beam on" period, the MLC controller receives information about delivered MUs approximately every 50 ms (this implies the sampling frequency is fixed at 20 Hz)[9,10] and uses this information to control the radiation beam on/off status for each segment. This communication delay results in the beam being turned off approximately 50–80 ms too late for all the segments when controlled by the MLC controller.[11] Especially impacted are the first and last segments that tend to have higher and lower MU than planned. This phenomenon is commonly referred to as the "overshoot/undershoot" for the first and last segments, respectively.[11] The last segment receives a smaller dose because the total beam control system turns the beam off when the total planned dose is reached.

The impact of the overshoot/undershoot phenomenon has been studied in the literature and has been found to be directly linearly proportional to the dose rate.[7,10-12] The lower the dose rate, the lower the impact of the phenomenon. It is desirable to use a higher dose rate, for reasons including: increased patient throughput and the less time the patient is on the table, the smaller the potential for intrafraction motion.[13] Furthermore, less time on the table is convenient for the patient (patient comfort). There is also the argument, albeit debatable, that prolonged dose delivery may result in reduction in tumor cell killing.[14-16]

Researchers have also reported that the magnitude of the errors due to the overshoot and undershoot phenomenon may be small and the clinical implication has been reported to be negligible.[10,11] However, these studies were carried out with ionization chamber at a single isocenter point and did not provide a fluence analysis of dose distribution on the whole target. The objective of the current study was to evaluate the impact of the over/undershoot on SMLC IMRT plan quality assurance (QA) using two-dimensional (2D) diode array at two different dose rates and analyze the impact of plan modulation complexion score on the IMRT QA.

The main objective of this study was to evaluate the impact of radiation dose rate on the accuracy of step-and-shoot IMRT dose delivery, as measured using ArcCHECK™ using two dose rates: 300 MU/min and 600 MU/min. The secondary objective was to see the impact of plan complexity as defined by the number of segments on IMRT QA.

Material and Methods

Patients

Twenty cancer patients who were treated at our center using IMRT were randomly selected for this study. This study population included prostate (n = 8), brain (n = 1), head and neck (n = 7), vulvar (n = 2), rectum (n = 1), and lung (n = 1) cancer patients. This study was reviewed by the Marshfield Clinic Institution Research Board and received a consent waiver.

Linac: Varian 2300CD

The linac used in this study was the Varian 2300CD equipped with Varian Millennium 120-leaf MLC capable of IMRT delivery. Radiation can be delivered using different dose rates. Our departmental practice standard uses the dose rate of 300 MU/min for IMRT radiation delivery. However, the 2300CD has the capability to deliver the radiation at a dose rate of up to 600 MU/min.

Treatment planning

Our institution's standard patient simulation protocol was used for each patient. For example, head and neck patients were immobilized using the head frame and scanned supine. Computed tomography images were obtained using 3-mm slide thickness. The images were then transferred to the treatment planning system (TPS) where the gross tumor volume, as well as the appropriate organs at risk (OAR) were contoured.

The step-and-shoot IMRT treatment plans were generated with a commercial TPS, Pinnacle[3] version 9.4 (Philips Medical Systems, Madison, WI) with direct machine parameter optimization (DMPO) option that directly optimizes the shape and weight of each MLC segment. Minimum segment area and minimum segment MU were set to 4 cm^2 and 3 MU, respectively. The adaptive convolution dose calculation algorithm with inhomogeneity correction was used for all the plans. The planning grid was set at 0.2 cm × 0.2 cm × 0.2 cm and threshold was set at 0.6 g/cm^2. The number of treatment fields used was the same as suggested by the Radiation Therapy Oncology Group (RTOG) protocols. For example, prostate cancer patients were planned with typical seven fields and head and neck with nine fields. The planning objectives were following recommendations from RTOGs. Patients were prescribed a typical dose of between 180 cGy and 200 cGy per fraction.

Plan evaluation

ArcCHECK™ device

The *ArcCHECK™* device (Sun Nuclear Corporation, Melbourne, Florida) has been previously described in the literature.[17,18] It is a doughnut-shaped cylindrical acrylic phantom containing a 2D array of 1386 diodes arranged in a helical configuration with 1 cm interdiode spacing and 1 cm pitch (ArcCHECK™ User's Guide, Sun Nuclear Corporation, Melbourne, Florida). The active detector size of each diode is 0.8 mm × 0.8 mm. The phantom has an outer diameter of 26.6 cm and inner hole diameter of 15.1 cm, with the curved plane of the diodes at a distance of 10.4 cm from the center. The overall device length is 44.3 cm inclusive of 11.9 cm of electronics section and 32.4 cm is the length of the PMMA phantom. The active area detector array length is 21 cm. The PMMA buildup and backscatter is approximately 2.9 cm each

which translates to water equivalent depth of 3.3 g/cm^2. The *ArcCHECK*^{TM} was used with the cavity plug-in and the cradle supports the device during calibration and measurements. Marks on the outer surface of the cylinder were used to position the device in the isocenter. In this study, the axis of the cylindrical phantom was aligned with the gantry rotation axis.

After each measurement, the individual frames were corrected for diode leakage current and angular dependence. The processed frames were then summed and saved to disk. DICOM RT planned Dose file was then imported for comparison to an *ArcCHECK*^{TM}-measured file. The import filter extracted a cylindrical dose plane from the imported 3D volume for 2D dose comparison with the *ArcCHECK*^{TM} diodes. The device was calibrated for absolute dose measurement.

Gamma plan evaluation

To compare dose distributions between calculated and measured doses, a gamma analysis[19] was performed with 3% dose difference (of the maximum dose) and 3 mm distance-to-agreement (DTA) criteria as recommended by the American Association of Physicist in Medicine (AAPM) task group 119.[20] The gamma analysis was evaluated in terms of the number of diodes which satisfied specified tolerances of dose difference between calculations and measurements relative to the maximum value on the calculated dose map (normalization point) and DTA criterion. Only the diodes with the dose values larger than 10% of the maximum value on the dose map were included in the analysis. This threshold of 10% was proposed by the AAPM Task Group 119[20] for the gamma evaluation with 3%/3 mm criteria.

Data analysis

The measured variables, namely, gamma analysis percentage pass rate, MUs, and number of segments were expressed as mean values. A linear regression analysis was conducted to determine if any of these variables: MUs, total number of segments, and mean MU/segments was a predictor of gamma analysis percentage pass rate. Multiple regression analysis was used to determine whether the different variables were combined predictor of gamma analysis percentage pass rate. Pearson's correlation coefficient was computed and the correlation coefficient of >0.5 was considered significant and correlated. Student's *t*-test was used to determine if the gamma analysis percentage pass rate was different between the two groups of patient treatment planning QA. *P* value was calculated and statistical significance was set at $P = 0.05$. Microsoft Excel (Microsoft Corporation, Redmond, WA) was used to compile data and perform basic statistical tests for analyzing the data.

Results

In our institution, we set the minimum number of MU/segment in the TPS to 3. Reviewing all the plans in the study, more than 70% of the fields had at least one segment with 3 MU/segment. The mean total MU was 666.3/patient and mean segments was 86.9 segments/patient, with mean of 8.03 MU/segments.

Using the gamma index criteria of 3 mm DTA and 3% dose difference resulted in a mean percentage gamma pass rate of 94.9% (range: 89.8%–99.1%) and 93.5% (range: 85.7%–99.1%) for 300 MU/min and 600 MU/min dose rate, respectively. In 80% of the cases, there was a decrease in percentage gamma pass rate when the dose rate was increased from 300 MU/min to 600 MU/min. Using a less stringent constraint of 4 mm DTA and 4% resulted in a mean percentage gamma pass rate of 98.6% (range: 95.8%–100%) and 98.1% (range: 95.0%–100%) for 300 MU/min and 600 MU/min, respectively. Evidently there is a decrease in gamma index percentage agreement with increase in dose rate for both 3 mm/3% and 4 mm/4% gamma index criteria. Using paired two-tailed Student's *t*-test analysis, the difference in gamma index pass rate with increase in dose rate was found to be statistically significant. The statistical result were as follows: t (19) =3.84, $P = 0.001$ for 3 mm/3% and t (19) =2.58, $P = 0.018$ for 4 mm/4%.

The results in the preceding paragraph show that the dose rate has an influence on the gamma index percentage pass rate comparing planned patient dose to measured patient dose using the *ArcCHECK*^{TM} device. We were interested in identifying other factors that could impact the percentage pass rate. Therefore, the association between the various parameters was computed using simple linear regression analysis, and the Pearson's correlation coefficients (r) are presented in Tables 1 and 2, with the significant correlations represented by asterisk. There was a weak, but significant association between the percentage pass rate at both dose rate and total number of segments [Figures 1 and 2]. As one would expect the total number of MU was significantly correlated with the total number of segments ($r = 0.59$).

The percentage pass rate for patient IMRT QA has been linked to the level of plan complexity. Therefore, attempts have been made in the literature to compute a modulation complexity score (MCS). The MCS proposed by McNiven *et al*.[21] incorporates information from the treatment planning such as variability in leaf position, degree of irregularity in field shape, segment weight, and area into a single score ranging from 0 to 1. We attempted to find a simple planning complexity

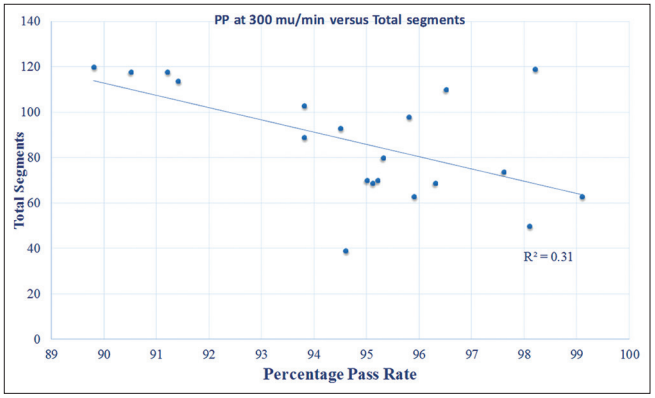

Figure 1: Gamma analysis percentage pass rate for 300 MU/min dose rate versus the total number of segments per treatment plan

Table 1: Linear correlation coefficients: The gamma analysis percentage pass was computed using gamma criteria of 3 mm DTA and 3% dose difference

	PP at 300 mu/min	PP at 600 mu/min	Prescription	Total MU	Total segments	Number of fields	MU/segment
PP at 300 MU/min	1						
PP at 600 MU/min	0.919*	1.000					
Prescription	−0.225	−0.274	1.000				
Total MU	−0.137	−0.143	−0.087	1.000			
Total segments	−0.557*	−0.572*	0.224	0.593*	1.000		
Number of fields	−0.198	−0.155	−0.254	0.599*	0.522*	1.000	
MU/segment	0.517*	0.550*	−0.276	0.123	−0.712	−0.169	1

PP: Percentage pass, MU: Monitor unit, *: Significant correlation

Table 2: Linear correlation coefficients: The gamma analysis percentage pass was computed using gamma criteria of 4 mm DTA and 4% dose difference

	PP at 300 MU/min	PP at 600 MU/min	Prescription	Total MU	Total segments	Number of fields	MU/segment
PP at 300 MU/min	1						
PP at 600 MU/min	0.823*	1.000					
Prescription	−0.177	−0.310	1.000				
Total MU	−0.111	−0.100	−0.087	1.000			
Total segments	−0.490*	−0.501*	0.224	0.593*	1.000		
Number of fields	−0.160	−0.060	−0.254	0.599*	0.522*	1.000	
MU/segment	0.457*	0.469*	−0.276	0.123	−0.712	−0.169	1.000

PP: Percentage pass, MU: Monitor unit, *: Significant correlation

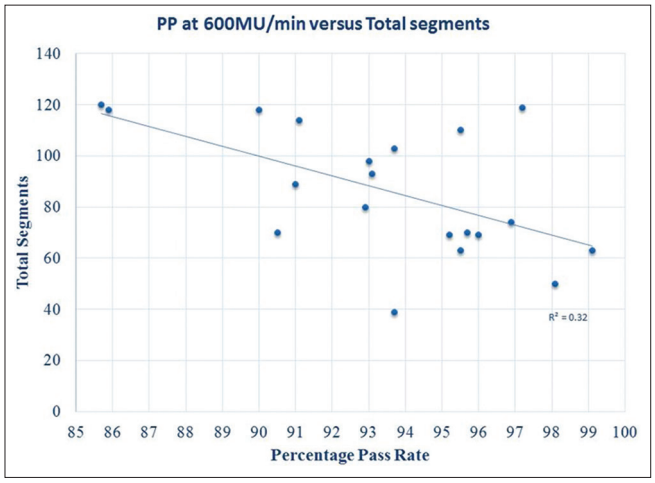

Figure 2: Gamma analysis percentage pass rate for 600 MU/min dose rate versus the total number of segments per treatment plan

score without access to segment descriptors like area and its association with percentage pass rate. Multiple regression analysis was computed with the percentage gamma pass rate as the dependent variable and the independent variables were: total number of MU, total segments, prescription dose per fraction, and the number of treatment fields. For 3 mm/3% at 300 MU/min dose rate, the total regression analysis coefficient was r = 0.63 and the only significant predictor was the total number of segment (P = 0.039). Similarly, at 600 MU/min dose rate, the total regression coefficient was r = 0.60 and the only significant predictor was the total number of segments (P = 0.049).

It has been documented that the magnitude of the overshoot is dependent on the number of MU/segment.[10,11] We normalized the total MU by the number of segments. We found a positive correlation between the percentage pass rate and mean MU/segment, r = 0.52 and r = 0.57 for 300 MU/min and 600 MU/min, respectively. There was a negative, but not significant correlation between the difference between the percentage pass rate at 300 MU/min and 600MU/min and the mean MU/segments.

Discussions

Effect of dose rate

The validation of patient dose as compared to the planned dose is an IMRT QA recommendation of many international bodies including AAPM[1] and ASTRO.[22] Various ways of measuring this patient QA have been studied since the introduction of IMRT and the current techniques include point dose measurement using ionization chamber, radiographic film, radio-chromic film, computed radiography, diode arrays, ionization chamber arrays, and portal dosimetry.[23,24] These techniques have been reviewed by the AAPM task group report number 120.[24] The *ArcCHECK*™ with its diode detector arrays is now an established and validated tool for patient IMRT QA.[17,18,25] Our mean gamma pass rate of 94.9% using 3 mm/3% gamma criteria measured with the *ArcCHECK*™ is similar to those reported by Petoukhova *et al.*[17] The accepted standard for conventional radiation therapy is that the dose delivered to the patient should be within 5% of the planned dose.[26] However, IMRT is more complex than traditional 3D conformal radiation

therapy (3DCRT), and high delivery accuracy is still expected all the same.

The factors affecting the accuracy of dose delivery in IMRT are multifactorial and include both TPS and machine errors. The machine errors have been identified by AAPM task group report[1] to include: MLC leaf positional accuracy, MLC control issues, MLC characteristics and transmission issues, and machine performance for small MU delivery. Researchers have tried to address some of these sources of inaccuracy in IMRT delivery. For example, Li *et al*.[27] studied the beam delivery system and found that the extra-focal source, MLC leaf thickness, leakage, tongue-and-groove structure, and leaf offsets can contribute up to 8% in the mean dose uncertainty.[27] The over/undershoot phenomenon is also a consequence of the delivery system and can also affect the dose delivery accuracy. This phenomenon is directly related to the dose rate.[10,11,28] The fact that we observed a significant improvement in percentage pass rate with decrease in dose rate is an indirect evidence of the impact of over/undershoot effect on dose delivery accuracy. We observed a 1.5% improvement in gamma percentage pass rate with a decrease in dose rate.

Other researchers have documented these effects on dose delivery accuracy. Ezzell and Chungbin[11] concluded that since the MU errors due to the over/undershoot phenomenon do not tend to accumulate, the sum total effect is not significant in high-dose region. While this is contrary to our findings, it is worth noting that the Ezzell and Chungbin's dosimetry was done using Kodak films known for limited dynamic range. To prevent saturation on the film, the plan MU had to be reduced. Xia *et al*.[10] also concluded that since the small MU segments were spread out throughout the entire IMRT fields, the overshoot and undershoot phenomenon was clinically insignificant. Similarly, it is worth noting that their dosimetry was carried out with ionization chamber. They found that the dose difference was within 2% between the measured and calculated doses in a relatively uniform high-dose region. Stell *et al*.[12] also reported the MU errors in implementing SMLC using Varian 2100CD. They analyzed the dose errors using log files and found that the dose differences between the original and recalculated plans were within 3%. No actual measured dose was conducted.

Our study is the first study that had specifically look into how the dose rate affects the patient IMRT QA gamma percentage pass rate. Our linac was commissioned for IMRT and the machine characteristics met the AAPM[1] recommendations. In particular, the dose/MU was found to be very linear ($r = 0.99$).

Effect of low monitor unit

Another suggestion that has been put forward to minimize IMRT inaccuracy due to MU delivery errors is to limit the minimum number of MU/segment. It is worth mentioning that the minimum MU was very critical in the early days of IMRT using the Corvus TPS. This is because the TPS generated segments with <1 MU. It was shown by Ezzell and Chungbin[11] that in some instances these segments with low MU were skipped altogether because of the overshoot phenomenon.

In addition to its effect on MU errors, small MUs are associated with a high degree of uncertainties.[29] Most investigators agree that dose delivery accuracy with small MU segments is machine specific; thus, individual institutions are advised to evaluate the characteristics of small MU settings before IMRT commissioning.[28] There have been a few studies addressing the photon beam characteristics at low MU, including dose linearity, stability of flatness, and symmetry.[29,30] Using a Varian 21EX, Kang *et al*.[30] observed that as the MU approached 1 per segment, the beam output increased up to 2% for 300 MU/min and 4.5% for 600 MU/min. They suggested that limiting the MU per segment to 7 or higher for 600 MU/min will result in <1% dose variation. Another study for segments with 400 MU/min on a Varian 2100C suggested segments of larger than 5 MU for the enhanced dose accuracy.[11] Grigorov *et al*. suggested that overall, to acquire sufficient beam start-up time, larger MU/segment and lower dose rates should be used.[8]

We found as part of our IMRT commissioning that limiting the minimum number of MU/segment to 3 provided the best dose accuracy per segment. Also, the accuracy of the machine output as a function of dose rate was found to be highly stable with a variation of < 0.4% between 300 MU/min and 600 MU/min dose rates.

Plan complexity

Another suggestion for IMRT delivery accuracy is to limit the degree of modulation.[21,31] The complexity of IMRT plans arises from beam modulation. Most IMRT plans require a large number of small and/or irregularly shaped beam segments to achieve high-dose conformity. These small beam segments carry higher dose uncertainties than those found in the large fields used in 3DCRT. In the treatment planning process, the beam complexity increased as the minimum segment area decreased and as the number of optimization iterations and the maximum number of segments increased.[32] Overly modulated fields can increase beam-on time and may be mechanically more challenging to deliver. Longer beam-on time increases integral dose to OAR due to inter- and intraleaf transmission leakage and scatter.[31] Highly modulated fields may also be more likely to suffer from tongue-and-groove effect.[27] Overly modulated fields may suffer from the interplay effect of MLC position and moving target. A study by Jiang *et al*.[33] indicated that many step-and-shoot IMRT treatment plans delivered today are more complex than necessary and can be simplified without sacrificing plan quality.

One indicator of the level of modulation is the number of segments per treatment. We found that the percentage gamma pass rate was inversely related to the number of segments ($r = 0.45$). This finding has been supported by others like Létourneau *et al*.[34] and Stell *et al*.[12] Létourneau *et al*.[34] found that the disagreement between the measured and calculated dose maps increases generally with the number of segments per beam and with the use of small segments delivering an appreciable fraction of the MUs. It is difficult to set fast rules in terms of required number of complexity for

each plan. This is because different clinical treatment sites have an inherent difference in the level of complexity that would be required to create a clinically acceptable plan, based on the differences in typical target shape, size, and location with respect to critical structures. However, the planner should still exercise judgment in terms of the level of complexity. It should be a red flag if a simple shaped target has a high number of segments.

New TrueBeam™ problem limited to the C-series

One obvious solution to the problem of the overshoot and undershoot is to improve the communication between the linac and MLC controllers. This is a solution that has been implemented in the new Varian TrueBeam™.[7,35] The new generation Varian TrueBeam™ linacs (Varian Medical Systems) has an integrated linac and MLC control system that communicates with each component retrospectively every 10 ms. This information is then used to prospectively instruct each component for the subsequent 10 ms and 20 ms to synchronize the planned and actual treatment delivery. Li *et al.* reported that the TrueBeam™, as compared to the Trilogy® has improved dose delivery accuracy of SMLC fields, particularly for low-dose segments (1 or 2 MU), at high dose rates of up to 600 MU/min, with no obvious overshoot or undershoot trend.[7] Their finding have recently been supported by the study of Agnew *et al.*[35] It is worth noting that with the implementation of volumetric-modulated arc therapy (VMAT) on Varian C-series, traditional IMRT using SMLC will less frequently be used and the overshoot/undershoot problem will be less significant.

Conclusions

For Varian C-series, the accuracy of the dose measured compared to the plan as evaluated using *ArcCHECK™* is dependent on the dose rate. This can indirectly be accounted for by the effect of the over/undershoot phenomenon.

To limit the impact of dose rate effect on measured dose, it is highly suggested that the number of mean MU/segment should be increased. In other words, highly modulated treatment plans should be avoided as possible.

IMRT requires better accuracy in every respect of treatment, including patient setup and beam characteristics; accumulated and combined errors make up the final treatment error that should be minimized as much as possible. It is necessary that any apparent error, even minute, must be minimized if possible. In this respect an error from dose rate needs to be reduced by using lower dose rate in the IMRT planning process.

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Conflicts of interest

There are no conflicts of interest.

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