Determination of Multileaf Collimator Positional Errors as a Function of Dose Rate, Speed, and Delivery Interruption for Volumetric-Modulated Arc Therapy Delivery

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Abstract

Aim: To determine the multileaf collimator positional error (MLC-PE) during volumetric modulated arc therapy (VMAT) delivery by studying the time-dependent MLC velocity in mathematically derivable trajectories such as straight line and conic sections. Materials and Methods: VMAT delivery is planned in a way that MLCs are moving in a locus which can be defined by mathematical functions such as linear, parabolic, or circular velocity (PV or CV). The VMAT delivery was interrupted either once or multiple times during the delivery and projection images of the same were acquired in electronic portal imaging device. MLC-PE was then analyzed as a function of dose rate (DR), and MLC speed (SP) and number of interruptions in treatment delivery. In VMAT delivery with linear MLC motion, the delivery was interrupted either once (linear motion single interruption) or multiple (three) times (linear motion multiple interruptions). For PV and CV MLC velocity, the MLC motions are interrupted multiple times. Results: The maximum individual error obtained (DR of 35 MU/min, SP of 2.0 cm/s) was 1.96 ± 0.1 mm. Only 4.4% of MLCs showed ≥ ±1 mm positional error. When the treatment delivery is interrupted multiple times in VMAT delivery, the influence of interruption in MLC-PE overwhelmed the influence by DR and SP. For a sub-group analysis of independent and dependent variables, the mean MLC-PE was 0.18 ± 0.4 mm 0.19 ± 0.42 mm, respectively. Conclusion: Determination of MLC-PEs using a mathematical function without approximation indicates that MLC-PE is not a function of MLC speed. In less than 5% of the studied scenarios, the MLC-PE exceeds its tolerance value (±1 mm). The MLC-PE is significantly less in modern machines due to advancements in the delivery mechanism.

Keywords: Electronic portal imaging device, multileaf collimator positional error, task group report-142, volumetric-modulated arc therapy

INTRODUCTION

Volumetric-modulated arc therapy (VMAT) delivers a highly conformal and uniform dose to the target while minimizing dose to organs at risk. VMAT is an advanced form of intensity-modulated radiation therapy (IMRT), in which the machine gantry keeps rotating during the treatment delivery while the dose rate (DR), gantry speed and leaf positions of the multileaf collimator (MLC) are modulated to achieve the desired dose distribution.[1] The significant potentiality of IMRT by rotational methods has been recognized over the last decade.[2,3] The original form of rotation therapy was given in 1982 by Brahme et al. by solving the integral equation.[4] Different vendors have different control mechanisms to handle the VMAT delivery system. All the available theoretical derivations in the published literature are based on the Varian system and showed that VMAT delivery is controlled by two parameters, MLC position as a function of delivered MU (M), and gantry angle as a function of cumulative MU θ (M).[5] Rangaraj et al. showed that VMAT delivery can be represented by MLC position as a function of gantry angle A(θ) and shown MU as a function of gantry angle M(θ), where A is the aperture created by MLC, M is

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delivered MU and $\theta$ is the gantry angle. It may appear that proposed solutions by \((A[\theta]: M[\theta])\) and are different \((A[M]: \theta[M])\), but if we analyze these carefully, these two different representation are in fact same.\(^{[5,7]}\) There are three variables in VMAT: gantry angle, delivered MU (which is a function of DR), and aperture position (which is a function of DR). Out of these three variables, two of them need to be expressed as an independent function of the third variable.\(^{[1]}\) Considering delivered MU as an independent variable and expressed aperture (A) and gantry angle (\(\theta\)) as a dependent variable, where specified aperture and gantry angle as dependent variables as a function of delivered MU.\(^{[5,7]}\) One could also specify the solution as \(M (A): \theta(A)\). The important point is \(M, A, \) and \(\theta\) are all functions independent of time. It may happen that both of the given solutions \(A(\theta): M(\theta)\) or \(A (M): \theta(M)\) satisfy independently in two different times (temporally separated), therefore it is essential to incorporate the time as an independent variable in the solution.

The clinical implication of rotational motion may influence the MLC positional error (MLC-PE) during the gantry motion enabled dose (VMAT) delivery. However, these forces are small in magnitude and they act orthogonal to the motion of MLC, hence do not affect the MLC position. MLCs are driven by motors using external torque. The error in the MLC position is proportional to the resultant force on the MLC. The primary aim of this study is to accurately measure MLC-PE during VMAT delivery and determine compliance with Task group report 142, and the secondary aim is to check the MLC position for a premature interruption during beam delivery. The stability of the gantry position for a prematurely interrupted beam is reported elsewhere.\(^{[8]}\)

**MATERIALS AND METHODS**

**Measurement of the multileaf collimator positional error during the volumetric modulated arc therapy delivery**

The treatment arcs in VMAT plans with the dynamic movement of MLCs are defined in terms of multiple segments or sub-fields; each of these sub-fields in turn is characterized by definite values of MU, gantry angle, and MLC speed. While transferring the VMAT plans from the TPS to the linear accelerator controller, these segments or sub-fields are translated as control points.\(^{[9]}\) This is a demerit of the controller system as discrete values of control points are approximated to enable continuous delivery. It was previously shown that this data translation is efficient and does not introduce any clinically significant errors in dose delivery.\(^{[8,9]}\) In VMAT delivery MLC speed, DR, and gantry speed are constant between two control points. Nevertheless, the temporal distribution of the MLC position/speed, DR/delivered MU, and gantry position/speed in VMAT plans is a complex function of time. The accelerator control mechanism carries out a linear interpolation of these parameters which results in a straight line. This approximation is mathematically inaccurate and hence has to avoided.

In a dynamic VMAT delivery, MLC motions follow complicated trajectories; therefore, to investigate these trajectories MLC positions must be measured accurately. To do this, a set of VMAT plans were created in which the movement of MLCs follow mathematically well-defined trajectories as a function of time, such as a straight line, circle, or parabola. To define the MLC position accurately, trajectory-specific interpolations were carried out so that mathematical approximation can be avoided. Figure 1 shows plots of MLC velocity versus time of circular and parabolic trajectories used for the experimental purpose and mathematical formulation. Three and six different velocities were used for the circular and parabolic trajectories respectively from the theoretically calculated velocities. MLC velocities are defined using discrete DRs of 35, 70, 140, 280, 560 MU/min and MLC speeds (SP) of 0.5, 1, 1.5, 2, and 2.5 cm/s. Details of the DR - MLC speed combination are presented in Table 1. The used MLC Speed and DR for circular, parabolic, and linear trajectories are presented in Table 1. All VMAT plans with definite MLC trajectories as shown in Figure 1, were created in Monaco (CMS Elekta, Sunnyvale, CA) treatment planning system, delivered using Elekta Axesse (Elekta AB, Stockholm, Sweden) linear accelerator and were acquired in electronic portal imaging devices (EPID) without any phantom or medium. EPID images were exported to OmniPro-I’mRT software (IBA, Schwarzenbruck, Germany) for image analysis and quantification.

**Detector (imager) and linear accelerator**

The maximum possible field size deliverable in the Elekta Axesse linear accelerator is 21 cm × 16 cm. Treatment fields are defined in Elekta Axesse only by the MLC system as there are no backup jaws. All delivered fields were acquired in the amorphous Si EPID called iView GT (Elekta, Stockholm, Sweden). The iView GT EPID can acquire signals in an area of 26 cm × 26 cm. Images are acquired in an array of 1024 × 1024 pixels with a resolution of 400 μm at the imager level and 250 μm at the isocenter. The EPID was precalibrated for systematic shifts and tilts to ensure that there was no confounding motion bias. Two different methods followed for MLC calibration: First, a major calibration, followed by a minor calibration. These methods are Elekta-defined and described elsewhere.\(^{[10-13]}\) Although the specified MLC leaf...
position accuracy in Elekta Axesse is 1 mm, which is on par with the recommendations of the American Association of Physicists in Medicine Task group report 142 (TG-142), experiments at the utilized MLC calibration methodology reveals that the system can achieve a far better accuracy level in the sub-millimeter range.\(^{[14-16]}\)

**Data acquisition**

It is more interesting to know the MLC positional errors in a clinical setting, where it has got a direct consequence on the dose delivery uncertainty. To determine the most accurate representation of the MLC position at any point of time, MLC velocity was given a definite mathematical form as a function of time as shown in Figure 1. VMAT delivery was interrupted in some intermediate position and projection images were acquired via the EPID imager. At the interruption point, the actual leaf position was calculated by analyzing the EPID images in OmniPro-I’mRT software - and called measured leaf position. Calculated leaf position for respective linear, parabolic, and circular velocities (PV and CV) was obtained from the linear, parabolic, and circular interpolations in the predefined MLC trajectory. MLC positional error was calculated by subtracting the measured MLC position (EPID) from the calculated MLC position. Only the left bank MLC was moved to keep the right bank fixed for the simplicity of calculation and measurement. MLC positional errors were calculated for 40 MLC leaves per field for 101 MLC defined fields with the total number of MLC’s evaluated for positional error were 4040; distributed as – linear motion - single interruption – 800 MLCs, linear motion multiple interruptions (LMMIs) – 2200 MLCs, CV - 400 MLCs and for parabolic motion 640 MLCs. For linear MLC motion, the leaves are interrupted either one time during the delivery (linear motion single interruption [LMSI]) or multiple (three) times (LMMI). For PV and CV MLC velocity, the MLC motions are interrupted numerous times. All measurements of 101 fields were delivered single time in a single day, with no repetition of any measurement. MLC positional errors were analyzed as an independent function of the DR and MLC Speed in independent subgroup analysis; and, as a dependent function of the DR and MLC speed in dependent sub-group analysis. Histogram analysis was carried out to find the mean, standard deviation (SD) of the MLC positional error, and number of MLC showing error greater than the TG-142 mentioned tolerance values of 1 mm.

**Results**

**Independent subgroup analysis**

Independent subgroup analysis based on DR and MLC speed was done to check the influence of these parameters on the MLC positional error. Figure 2a-d show the influence of MLC speed on MLC-PE and Figure 2e-h correspond to the dependence of the MLC-PE on DR. Mean MLC-PE and 95% confidence intervals (CI) were plotted as a function of the speed for CV, PV, LMMI, and LMSI values with MLC number as a parameter [Figure 2a-d]. The maximum MLC positional error obtained for CV, PV, LMSI, and LMMI were \(-0.75, 1.11, 0.78,\) and 0.37 mm, respectively. Mean MLC-PE for the same set was \(-0.30 \pm 0.15, 0.65 \pm 0.51, 0.23 \pm 0.24,\) and 0.15 ± 0.09 mm, respectively. Although the mean positional error does not show any dependence on speed the data obtained shows a larger SD for CV and PV at lower speed, and for LMSI at higher speed. CV (\(P = 0.9978\)) and LMMI (\(P = 0.4943\)) were found to have no correlation with MLC speed using Student’s \(t\)-test significant correlation at \(P < 0.05\). However, LMSI (\(P < 0.0001\)) and PV (\(P < 0.001\)) were found to be very strongly correlated with the speed, calculated using the Student’s \(t\)-test.

Analysis of the MLC-PE as a function of DR is presented in Figure 2e-h. We observed that for all the tested velocities, the CI of the mean of MLC-PE has relatively larger values at the

### Table 1: Multileaf collimator speed and dose rate used for creating different circular, parabolic, and linear multileaf collimator velocities

| Linear motion | Single interruption | Multiple interruption | Single interruption | Multiple interruption |
|---------------|---------------------|-----------------------|---------------------|-----------------------|
| DR (MU/min)   | MLC speed (cm/s)    | DR (MU/min)           | MLC speed (cm/s)    | DR (MU/min)           |
| 35 - 70       | - 35 -              | 70 - 2.24             | - 35 -              | - 35 -                |
| 140 - 280     | - 140 -             | 140 - 1.88            | 280 - 1.28          | 70 - 1.73             |
| 560 - 1.5     | - 560 -             | 280 - 1.88            | 560 - 1.28          | 70 - 2.24             |
| - 0.5 - 1     | - 1 -               | 280 - 2.24            | 140 - 1.41          | 1.05 - 1.41           |
| - 1 - 1.5     | - 1 -               | 560 - 1.28            | 140 - 2             | 1.05 - 1.41           |
| - 1.5 - 2     | 1.5 - 2             | 560 - 1.88            | 140 - 2.45          | 1.05 - 1.41           |
| - 2 - 2.5     | 2 - 2.5             | 560 - 2.24            | 280 - 1.41          | 1.05 - 1.41           |
| 35 - 35.5     | - 35 - 35.5         | 70 - 1.73             | - 35 - 1.73         | 280 - 1.73            |
| 35 - 1.5      | - 35 - 1.5          | 280 - 2.24            | 560 - 1             | 280 - 2.24            |
| 35 - 2        | - 35 - 2            | 560 - 1.73            | 560 - 1.73          | 280 - 2.24            |
| 70 - 70       | - 70 - 70           | 560 - 2.24            | 560 - 2.24          | 560 - 2.24            |
| 70 - 1.5      | - 70 - 1.5          | - 70 - 2             | - 70 - 2.5          | - 70 - 2.5            |
| 140 - 140     | - 140 - 140         | - 140 - 1             | - 140 - 1.5         | - 140 - 1.5           |
| 140 - 1.5     | - 140 - 1.5         | - 140 - 2             | - 140 - 2.5         | - 140 - 2.5           |
| 280 - 280     | - 280 - 280         | - 280 - 1             | - 280 - 1.5         | - 280 - 1.5           |
| 280 - 1.5     | - 280 - 1.5         | - 280 - 2             | - 280 - 2.5         | - 280 - 2.5           |
| 560 - 0.5     | - 560 - 0.5         | - 560 - 1             | - 560 - 1.5         | - 560 - 1.5           |
| 560 - 1.5     | - 560 - 1.5         | - 560 - 2             | - 560 - 2.5         | - 560 - 2.5           |

**DR**: Dose rate, **MLC**: Multileaf collimator, **CV**: Circular velocity, **PV**: Parabolic velocity.
lower DR compared to the higher DR. For a lower DR, MLC positional error is also higher. As an independent function of DR, the highest positional error, for CV, PV, LMSI, and LMMI were found to be −0.94, 0.99, 0.77, and 0.37 mm, respectively. The mean positional error in the DR analysis for all velocities was found to be \(-0.82 \pm 0.35, 0.24 \pm 0.65, -0.21 \pm 0.23, \) and \(-0.11 \pm 0.15 \) mm for CV, PV, LMSI, and LMMI, respectively.

Independent subgroup analysis is further elaborated in Figure 3a. The overall independent analysis of the MLC positional error analyzed for DR and speed is presented in Figure 3a. The analysis with velocity as an independent variable resulted in the highest mean MLC-PE of 0.96 ± 0.962 mm obtained for PV 1.41 cm/s. Analyzing based on DR, the highest positional error of 0.85 ± 0.14 mm was obtained for PV with DR of 140 MU/min.

**Dependent subgroup analysis**

In the dependent subgroup analysis, shown in Figure 3b, the MLC-PE was analyzed as a conjugate function of DR and MLC speed (SP). The highest error (1.96 ± 0.1 mm) was obtained in the case of an LMSI (DR of 35 MU/min, SP of 2.0 cm/s). The second highest MLC PE (0.92 ± 0.95 mm) was obtained for the combination of PV DR and MLC speed of 140 MU/min and 1.41 cm/s. Out of 68 combinations of DR and MLC speed, 50 cases showed an error within ±0.5 mm. Only one of the 64 combinations, for LMSI (DR of 35 MU/min: SP of 2 cm/s), experienced an error of more than 1 mm in the MLC position. This constitutes 1.5% of the total number of cases analyzed. The overall mean MLC-PE was 0.19 ± 0.42 mm.

**Statistical analysis**

Statistical analysis of the independent and dependent sub-groups is presented in Table 2. The statistical analysis was performed following the Student’s *t*-test using SAS software. The independent variable analysis was performed for beam interruption, dose, and velocity for linear motion and multiple interruptions. The effect of the interruption overwhelmed the effect of dose and velocity with a significance levels of \(P < 0.0001\) and \(P = 0.9461\) and \(P = 0.4055\) respectively. Similar results were observed in the investigation considering the dependent variables, as well, resulting in significance levels of \(P < 0.0001\) for interruption; \(P = 0.9635\) for dose, and \(P = 0.4943\) for speed. We incorporated a parameter called estimate in the statistical analysis. This parameter indicates the increase (or decrease) of MLC positional error associated with a variable while another variable was taken as a constant. For example, in the dependent variable analysis, the estimate for interruption was 0.0648. This indicates that after adjusting the speed and dose, 1-unit increase in interruption is associated with 0.0648-unit increase in the MLC-PE. This parameter “estimate” is the gradient between two variables while treating other variable(s) as constant. The independent variable analysis for LMMI showed an estimate of 0.0652,
0.000004, and 0.017 for the interruption, DR, and MLC speed, respectively. For other tested velocities in the case of dependent and independent variable analysis, the DR and speed were both found to be statistically significant except for a single point. In the dependent variable analysis of circular velocity, the dependency of the speed on MLC-PE was found to be statically insignificant ($P = 0.9643$).

**Histogram analysis**

Figure 4 demonstrates the MLC-PE histograms for linear MLC motion with a single interruption (LMSI) [Figure 4a], linear MLC motion with multiple interruption (LMMI) [Figure 4b], circular MLC velocity [Figure 4c], and parabolic MLC velocity [Figure 4d].

The MLC-PE histogram is shown in Figure 4a for single interruptions in the linear velocity of the MLC. The MLC-PE shows two degenerate peaks, and hence a bimodal distribution. The MLC-PE peaks at $+0.23$ mm (SD = 0.476 mm). However, we could not find the physical reason for the distribution having a second peak at 2 mm and no significant MLC-PE was observed from 0.8 to 1.7 mm. One of the possible reasons for two degenerate extremes could be systematic errors in the measurement. However, the other three experiments performed with the same settings do not show any such trend for the measured MLC-PE. MLC linear velocity with multiple interruptions shows a mean MLC-PE of $0.15 \pm 0.623$ mm (1σ). MLC motion with circular and parabolic velocities show mean MLC-PEs of $0.32 \pm 0.623$ mm (1σ) and $0.65 \pm 0.68$ mm (1σ), respectively.

The situation became more interesting when the MLC-PE histogram rows are paneled by the DR and the MLC speed is planned by column. The reason for the second peak at 2 mm for LMSI can now be explained. Figure 5a, cell (1, 4) (using standard matrix notation), represents the DR 3 MU/min and MLC speed 2 cm/s and produces a peak at $\approx 2$ mm. For any other combination of DR and MLC speed the MLC-PE peaks at around 0.0 cm, leading to two peaks in Figure 4a for LMSI. For multiple interruptions in linear velocity (LMMI) [Figure 5b], MLC-PE at a DR of 35 MU/min shows a two-fold degeneracy with two distinct peaks for all velocities (1, 1.5, 2 and 2.5 cm/s). The MLC-PE shows a three-fold degeneracy for the DR 70 MU/min DR, and speed 1.5 and 2.5 cm/se. The degenerate peaks are distinctly separated from each other, indicating a discreet
The highest MLC speed, lowest DR combination does not result in maximum MLC-PE. The largest MLC-PE obtained for linear MLC motion with single interruption is 2.16 mm for the combination of DR, 35 MU/min and velocity, 2 cm/s [Figure 5a, cell (1, 4)]. In the case of LMMI, the highest MLC-PE obtained was −1.59 mm, associated with DR, 70 MU/min and SP 2.5 cm/s. For circular velocity, the maximum MLC-PE obtained was −0.78 mm, associated with DR 70 MU/min and MLC velocity 2.24 cm/s [Figure 5c cell (1, 4)]. For parabolic MLC movement, the maximum MLC-PE (1.3 mm) has occurred in the scenario in which the DR was of 140 MU/min and speed was of 1.41 cm/s [Figure 5d cell (2, 1)]. Out of 4040 observations, 4.4% (178 out of 4040 observations) MLCs exceed the American Association of Physicists in Medicine’s (AAPM) TG-142 specified tolerance of 1 mm.\[17,18\]

**Table 2: Statistical analysis of the dependent and independent subgroup analysis**

| Tested speed | Parameter | Estimate | SE  | t    | Pr>||t| | 95% CI | Analysis method |
|--------------|-----------|----------|-----|------|---------|-----------------|----------------|
| LMMI         | Interruption | 0.065 | 0.014 | 4.55 | <0.001 | 0.04-0.09 | Independent variable |
|              | Dose      | 0.000 | 0.000 | 0.07 | 0.946 | 0.00-0.00 | Independent variable |
|              | Speed     | 0.017 | 0.021 | 0.83 | 0.405 | 0.40-0.65 | Independent variable |
|              | Interruption | 0.065 | 0.014 | 4.52 | <0.001 | 0.04-0.09 | Dependent variable |
|              | Dose      | 0.000 | 0.000 | -0.05 | 0.963 | 0.00-0.00 | Dependent variable |
|              | Speed     | 0.014 | 0.021 | 0.68 | 0.494 | -0.03-0.05 | Dependent variable |
| LMSI         | Dose      | 0.000 | 0.000 | -4.60 | <0.001 | 0.00-0.00 | Independent variable |
|              | Speed     | 0.338 | 0.028 | 12.25 | <0.001 | 0.28-0.39 | Independent variable |
|              | Dose      | 0.000 | 0.000 | -5.03 | <0.001 | 0.00-0.00 | Dependent variable |
|              | Speed     | 0.338 | 0.027 | 12.43 | <0.001 | 0.28-0.39 | Dependent variable |
| CV           | Dose      | 0.001 | 0.000 | 15.34 | <0.001 | 0.00-0.00 | Independent variable |
|              | Speed     | 0.160 | 0.044 | -3.61 | 0.003 | -0.25-0.07 | Independent variable |
|              | Dose      | 0.001 | 0.000 | 14.65 | <0.001 | 0.00-0.00 | Dependent variable |
|              | Speed     | 0.002 | 0.037 | 0.04  | 0.964 | -0.07-0.08 | Dependent variable |
| PV           | Dose      | 0.000 | 0.000 | 2.5   | 0.015 | 0.00-0.00 | Independent variable |
|              | Speed     | -0.386 | 0.027 | -14.03 | <0.001 | -0.44-0.33 | Independent variable |
|              | Dose      | 0.000 | 0.000 | 3.72  | 0.002 | 0.00-0.00 | Dependent variable |
|              | Speed     | 0.316 | 0.027 | 14.36 | 0.0001 | 0.44-0.33 | Dependent variable |

SE: Standard error, LMMI: Linear motion multiple interruptions, LMSI: Linear motion single interruption, CV: Circular velocity, PV: Parabolic velocity, CI: Confidence interval

**Figure 4:** Histograms analysis of MLC-PE for linear MLC motion with single interruption (LMSI) (a) Linear MLC motion with multiple interruption (LMMI) (b) Circular speed MLC speed (c) And parabolic speed MLC speed (d) MLC: Multi leaf collimator, MLC-PE: MLC positional error, LMSI: Linear motion single interruption, LMMI: Linear motion multiple interruption

**Figure 5:** Individual histograms analysis of MLC-PE for linear MLC motion with single interruption (LMSI) (a) Linear MLC motion with multiple interruption (LMMI) (b) Circular speed MLC speed (c) And parabolic speed MLC speed (d) Histogram rows are paneled by the DR and columns are paneled by the MLC velocity. MLC: Multi leaf collimator, MLC-PE: MLC positional error, LMSI: Linear motion single interruption, LMMI: Linear motion multiple interruption, DR: Dose rate

**Discussion**

The published literatures by Rangaraj et al. and Yu used aperture definition, delivered MU, and gantry angle to define
the VMAT delivery. Rangaraj et al. described VMAT delivery as aperture definition (MLC position) and delivered MU as a function of gantry angle \((A[\theta]: M[\theta])\).\(^{[7]}\) Yu described it as aperture and gantry angle as a function of delivered MU \((A[M]: \theta[M])\).\(^{[5]}\) Although these two are different approaches, both lead to effectively similar solutions by using two of these three parameters as dependent variables and the remaining one as an independent variable. In both proposals, time was not considered as a parameter. The obtained solution is based on the hypothesis that the time parameter \((t)\) will be satisfied independently by the solution and reduces to \((A[\theta, t]: M[\theta, t])\) or \((A[M, t]: \theta[M, t])\). However, this hypothesis was not clearly mentioned in their solution. As time is not a variable in this solutions the approach turned out to be semi-empirical. Solving the Lagrangian formulation would be the mathematically appropriate method, as described by Sarkar and Basu.\(^{[19]}\)

We have not observed any linear dependence of the MLC positional error with either increase or decrease in the speed. However, previous researchers, Sonke et al. and Partridge et al. in their studies on the static gantry with DMLC delivery movement have claimed a linear relationship between the MLC-PE and the MLC speed.\(^{[12,16]}\) However, a similar trend is not observed for a rotating gantry VMAT delivery. In an inertial frame of reference, that is without any rotation, total force, and hence, the acceleration of any particle is a function of external torque only. The force-dependent MLC-PE is a linear function of the force and hence is the MLC speed. This trend was observed in the experiments performed by Partridge et al. and Sonkey et al. In our present work, the total force is not proportional to the external torque. As a result, we have not obtained any linear relationship between the MLC speed and the MLC positional error. This leads to two observations from the study. First, the presence of the pseudo force in the VMAT delivery does not influence the MLC motion. Second, in the case of rotational delivery, MLC-PE is a function of external torque only.

Although we have not observed any proportional relationship for MLC-PE with DR or MLC speed, a relatively higher MLC-PE was observed at a lower DR. This is because when the DR is lower MLCs are moving at a higher speed; therefore, a higher external force is delivered to the MLCs, eventually resulting in higher MLC-PE. It was found in through our study that the largest leaf position errors were not associated with the highest MLC speed. This result differs from the study by Partridge et al. and Ramsey et al.\(^{[16,18]}\) where Ramsey et al. stated that the largest MLC error was obtained for the largest MLC speed of 3 cm/s.\(^{[16,18]}\) It is important to note that Ramsey et al. described the MLC-PE for Varian 52 leaf MLC (Varian Medical system Inc, Palo Alto, CA) where the present experiment used an Elekta Beam Modulator MLC and the dynamic MLC control system has also evolved since the publication of this report.\(^{[18]}\) In 2001, Varian and Elekta, two different commercially available VMAT solutions, have an additional control mechanism hence different MLC movement mechanisms is observed.\(^{[20]}\)

AAPM task group report (TG-142) specifies 1 mm as the tolerance for MLC position.\(^{[14]}\) Although this recommendation was based primarily on manufacturer specifications, in this experiment it was found that 4.4% MLCs exceed the tolerance recommended by the AAPM TG-142. The degenerate peak in the histogram analysis for multiple interruptions in linear MLC motion can be observed only for lower DRs (35 MU/min and 70 MU/min), but for all velocities. Therefore, it can be concluded that MLC-PE degeneracy is an associated property of the DR alone and not of the MLC speed. Recently, several investigators have reported various methods of determining MLC positional error during arc therapy delivery.\(^{[9,21–25]}\) Tyagi et al. have done real-time monitoring of the MLC position of two sets of clinical treatment plans using an iCom client interface.\(^{[25]}\) The approximation involved in their experiment is with interpolated MLC positional values. In an actual VMAT delivery, the MLC loci are of complicated motion and no mechanism can predict the actual MLC position without an approximation.

The MLC loci used in our study is governed by a definite mathematical function; therefore, the approximation is not involved in predicting the leaf position at any point time during the motion. We observed a variation of 6 mm MLC-PE and 3° gantry positional error in binned DR mode of the Elekta linear accelerator. In our case, the linear accelerator was operated in the same binned DR mode at the lowest available DR and highest MLC speed without an observed MLC positional error exceeding 2 mm. Another article by our group indicated that in the most adverse conditions, the gantry position error does not exceed 1.2°.\(^{[15]}\) The operated MLC speed is very low (0.12–0.8 cm/degree), and when working at the highest speed (2.25 cm/s) we have obtained similar MLC positional errors.\(^{[25]}\) Agnew et al. validated the MLC delivery log-file analysis with EPID-based measurements for Varian TrueBeam and concluded that the log files might not detect the MLC positional error due to t-nut or motor faults.\(^{[23]}\) Fuangrod et al. tested the DMLC trajectory in real-time using EPID, and, Rowshanfarzad et al. verified the MLC performance of VMAT and IMRT using EPID imaging.\(^{[22,23]}\) Zhu et al. tested the VMAT delivery in static and rotational gantry motions using four different detectors: EPID, two different two-dimensional (2D) ion chamber arrays, and one cylindrical diode array.\(^{[24]}\) They have observed that the performance of the EPID imaging is superior compared to other detectors.\(^{[24]}\)

The above literature review indicates the superiority of EPID based measurements over log file analysis or detector-based systems such as 2D ion chamber array and diode detector assembly by Agnew et al. and Zhu et al.\(^{[20,24]}\) We put forward three points in support of the above claim. First, in an Elekta linear accelerator, the EPID sagging due to gravity is minimal because the EPID arm rests in a mechanical assembly and
does not have a provision to move along the gantry direction, as in the case of Varian linear accelerators. This advantage in construction makes Elekta EPID more stable against any spatial drift. Second, it can be stated that EPID is the ideal tool to check the MLC performance because of its geometrical position with the gantry. This makes the EPID panel always parallel to the MLC movement and hence the ipsilateral MLC (left) bank\textsuperscript{[15]} is always imaged by some part of the EPID (e.g. left side). Thirdly EPID offers significant resolution (400 µm) and is only comparable with that of the film (80 µm).

All other detectors, such as ion chamber and diode arrays offers resolution.\textsuperscript{[13,24]} However, the geometric position of EPID with the gantry has got its disadvantages also, as any systematic error in the MLC position can lead to errors in patient plan delivery.\textsuperscript{[15]} Although various authors have attempted to check the MLC position during VMAT delivery, recent literature does not address the relationship between the MLC speed and MLC-PE.\textsuperscript{[10,12,15,16,18,20-27]} In our experiment, the MLCs were interrupted while moving. This is to simulate and verify the situation of premature delivery termination and unplanned interruption during treatment delivery. This paper concludes that for premature delivery, the MLC positional error exceeds the TG-142 specified tolerance in only 4.4% of studied cases. Different researchers have investigated the dosimetric effect of such unplanned interruption of the treatment delivery for Elekta linear accelerators and concluded that the control mechanism, MOSAIQ sequencer (IMPAC Medical Systems, Inc., Sunnyvale, CA, an Elekta company), can resume the treatment without any significant dosimetric inaccuracy.\textsuperscript{[8,9]}

**Conclusion**

Our approach clarifies the dependence of delivery parameters on time in arc therapy and substantiates that MLC positional error is not proportional with MLC speed which contradicts the result from the earlier studies by Sonke et al. and Partridge et al.\textsuperscript{[12-16]} We observed significantly less MLC positional errors compared to earlier reports, probably due to recent significant improvements in the accelerator control mechanism. Although the mathematical formulation is generalized, the specific MLC characteristics indicate the good reproducibility of the Elekta MLC on par with the AAPM formal guideline, TG-142 report.

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**Conflicts of interest**

There are no conflicts of interest.

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