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NYU Langone Health

Validation of a Robust Enhanced Leaf Model for Beam-Matched Linear Accelerators: Impact of Physical Leaf Gap Variations

Soyoung Lee, PhD[1]; Paulina Galavis, PhD[1]; Siyoung Jang, PhD[2]

[1]NYU Langone Health, [2]Boston Medical Center, Boston University Chobanian & Avedisian School of Medicine

ABSTRACT

Purpose: This study characterized inter-machine variations in physical leaf gaps and associated MLC parameters, including dosimetric leaf gap (DLG) and leaf gap (LG), and provides practical guidance for robust ELM implementation through physical leaf gap adjustment.

Methods: Five TBs equipped with Millennium120 were grouped into GroupA (3TBs) and GroupB (2TBs). TBs within each group were dosimetrically matched and shared a common beam model. Variations in physical leaf gap, DLG, and machine-specific LG relative to the machine-averaged LG were evaluated. For Group B, physical leaf gap differences exceeding 0.050 cm were adjusted halfway toward the machine-averaged value. Clinical ELM models were validated for individual TBs using 3 mm narrow-MLC (nMLC), subsequent static-MLC (sMLC), and dynamic-MLC (dMLC) fields with 3 mm sweeping gaps over central- and off-axis up to 10 cm. GafChromic film measurements were compared with ELM-calculated profiles before and after adjustment using FWHM and 1D γ-analysis (2%/1mm, 10% threshold).

Results: Identical physical leaf gaps in Group A TBs resulted in DLGs and LGs differences < 0.02 cm and good agreement in MLC profiles comparisons. In Group B, physical leaf gap adjustment ~0.028 cm reduced DLG and LG differences, and achieved γ-passing rates > 95%, FWHM differences < 0.01 cm for nMLC tests, γ-passing rates > 98% for sMLC, and dose differences < 2% at the center of dMLC fields.

Conclusions: Robust clinical implementation of ELM requires explicit consideration of mechanical leaf gap variability, with additional validation using the MLC test fields to ensure clinical suitability.

NYU Langone Health

CONTACT

[name] Soyoung Lee
[organization] NYU Langone Health
[address] 160 E 34th St, New York, NY 10016
[email] Soyoung.Lee@nyulangone.org
[phone] 212-731-5883

INTRODUCTION

The Enhanced Leaf Model (ELM), introduced in Eclipse TPS v18.0 or later (Varian Medical Systems, Palo Alto, CA, USA), improves geometric representation of MLC leaf bodies and rounded leaf ends using divergent ray tracing. In earlier MLC modeling approaches, dosimetric leaf gap (DLG) and/or leaf transmission (LT) were often empirically determined to optimize agreements between calculated and measured doses. ELM MLC parameters are derived from LT and sweeping-gap measurements performed on the corresponding treatment unit while incorporating machine-specific mechanical leaf calibration.

The purpose of this study was to quantify the dependence of ELM-derived parameters on mechanical leaf gap calibration across multiple beam-matched linacs and to evaluate the resulting dosimetric impact of inter-machine variability. We investigated a clinically practical approach using machine-averaged ELM parameters with converged mechanical leaf gap settings to maintain robust and interchangeable delivery in a multi-linac environment.

METHODS AND MATERIALS

Five TrueBeam linacs equipped with Millennium 120 MLC were grouped into two clinical sites (Group A: three linacs; Group B: two linacs) sharing matched beam model within each group. Variations in physical leaf gap, DLG, and ELM-derived leaf gap (LG) were evaluated. Physical leaf-gap differences exceeding 0.05 cm were mechanically adjusted while maintaining a machine-averaged clinical ELM model. ELM performance was evaluated on each linac using three MLC test plans: dynamic MLC (dMLC), narrow MLC (nMLC), and static MLC (sMLC). Following the physical leaf-gap adjustment, DLG and LG values were verified. Also, the central doses of dMLC fields were measured using an ionization chamber (CC04) and compared with ELM-calculated doses.

1) dMLC: A 2 cm field generated with overlapping 3-mm sweeping gaps was delivered at CAX, 4, and 8 cm OAX. The central dose of the dynamic sweeping-gap field was used to assess gap-dependent integral dose response.[1]
2) nMLC: A 3 mm MLC slit delivered at CAX, 5 and 10 cm OAX to evaluate penumbra and small-aperture sensitivity to leaf gap variation.[1]
3) sMLC: Four sequential 4 x 20 cm^2 MLC segments were delivered with intentional overlap between adjacent subfields to enhance sensitivity to leaf gap variation, and to evaluate dosimetric impacts at junctions associated with rounded leaf ends.[1]

Table 1. MLC parameters in TPS before and after version 18.

DLG-based MLC Model Parameters (TPS before V18)	ELM Model Parameters (TPS V18 and up)	MLC Measurements
• Leaf Transmission (LT): represents homogenous attenuation through the thin layer. • Dosimetric Leaf Gap (DLG): represent the offsets between opposing leaf accounting rounded leaf-tip.	• Leaf Transmission (LT): represents average attenuation through the leaf body including screw cutout. • Leaf Gap (LG): iteratively optimized from the sweeping-gap measurements.[2]	1) Open 10 x 10 cm^2 field, 2) transmission fields blocked by MLC bank A and bank B, 3) three sweeping-gap fields with gap widths of 4 mm, 6 mm, and 20 mm on a 10 x 10 cm^2 field size.

RESULTS

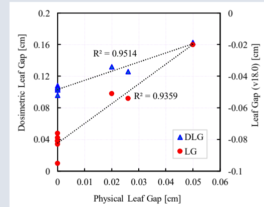

Figure 1. DLG and LG values for five linacs with varying physical leaf gaps from 0 to 0.05 cm. Across all five linacs, both DLG and LG demonstrated strong linear dependence on the physical leaf gap ($R^2 > 0.93$) across clinical sites.

In Group A, ELM-derived MLC parameters showed minimal variation, with LG values agreeing within 0.02 cm. Film measurements demonstrated excellent agreement between calculated and measured dose distributions for all MLC test fields.

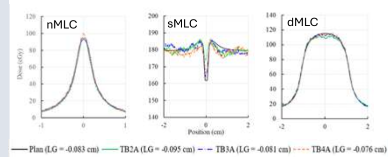

Figure 1. MLC tests for Group A TBs: In nMLC test, all measured profiles resulted in gamma passing rates (2%/1 mm, 10% threshold) of 98-100% and FWHM derived from measured and calculated profiles were highly consistent, resulting in differences below 0.2 mm. In sMLC test, calculated and measured profiles demonstrated good overall agreement, including at the leaf junction regions. The mean central-dose difference relative to the calculated profile was 4.1%, 2.0%, and 3.0% for TB2A, TB3A, and TB4A, respectively. In dMLC test, across all positions, the chamber-measured central doses differed from the calculated doses by an average of -1.7%, 2.3%, and 2.8% for TB2A, TB3A, and TB4A, respectively.

In Group B, an initial 0.05 cm difference in physical leaf gap resulted in substantial discrepancies in dMLC tests, including central dose deviations of −7.5% and +5.0% relative to calculated doses and a corresponding ~0.05 cm difference in dMLC field width on the EBT4. Following mechanical leaf-gap adjustment, ELM-derived parameters converged and dosimetric agreement improved markedly.

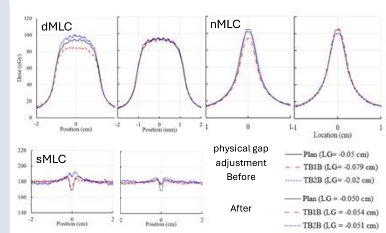

Figure 2. MLC tests for Group B TBs. In nMLC test, 100% γ-passing rate for TB1B before and after adjustment, and 90.3% and 99.8% for TB2B before and after adjustment; In dMLC, the physical gap adjustment from 0.0 to 0.026 cm on TB1B changed the dose at the field center of 5.9% on average over the CAX and OAXs, and the adjustment from 0.05 to 0.02 cm on TB2B changed the dose of -5.5% on average. In sMLC test, The mean central-dose difference was 0.86% for TB1B and 9.83% for TB2B. Following gap adjustment, agreement improved, with mean central-dose differences of 2.97% and 0.77% for TB1B and TB2B, respectively.

Table 1. MLC parameters for each linac. The LT and LG values for each machine were derived from individual MLC measurements for ELM configuration in Eclipse v18.0. The clinical ELM was obtained by averaging of individual MLC measurements. The DLG values for each machine were independently calculated from the MLC measurements. Additionally, the LT and DLG values used for the conventional DLG-based MLC model in v15.6 are presented.

Group A				
Linac#	LT	Physical Gap (cm)	DLG (cm)	LG (cm)
TB2A	0.015	0.00	0.096	– 0.095
TB3A	0.015	0.00	0.103	– 0.081
TB4A	0.014	0.00	0.108	– 0.076
Clinical ELM model (v18.0)	0.015			– 0.083
Clinical DLG model (v15.6)	0.015		0.125	

Group B		Before adjustment			After adjustment		
Linac#	LT	Physical Gap (cm)	DLG (cm)	LG (cm)	Physical Gap (cm)	DLG (cm)	LG (cm)
TB1B	0.013	0.00	0.103	– 0.079	0.026	0.126	– 0.054
TB2B	0.013	0.05	0.163	– 0.020	0.02	0.132	– 0.051
Clinical ELM model (v18.0)	0.013			– 0.050			
Clinical DLG model (v15.6)	0.014		0.130				

DISCUSSION

The study results indicated that reducing the physical leaf gap discrepancies between linacs, followed by ELM commissioning, provides a robust approach for multi-linac MLC and beam modelling as empirical tuning of MLC parameters to improve agreement with measurements does not harmonize MLC performance across beam-matched linacs.

- A 0.05 cm difference in physical leaf gap between Group B linacs produced approximately 0.06 cm differences in both DLG and LG values and resulted in dMLC dose deviations of up to 7.5%.

Among the validation MLC fields, the dMLC field demonstrated particularly high sensitivity to physical gap variability.

- a mechanical gap change of approximately 0.25-0.30 mm produced corresponding 5-6% variations in the central dose response of the dMLC fields.

CONCLUSIONS

Sub-millimeter differences in mechanical leaf gap calibration can produce clinically meaningful variations in dynamic MLC dose response under the ELM. Implementing a hybrid strategy that combines machine-averaged ELM parameters with harmonized mechanical leaf gap settings provides clinically robust approach for maintaining delivery consistency across beam-matched linacs. Dynamic sweeping-gap measurements offer a sensitive and time-efficient method for validating ELM performance and identifying residual inter-mahcine discrepancies. These findings provide practical guidance for institutions seeking to deploy ELM across multiple linacs while preserving clinical workflow, delivery interchangeability, and dosimetric consistency.

REFERENCES

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2. Varian Medical Systems, Inc. Enhanced Leaf Modeling Measurement Procedure, Document ID P1062983-002-B; Palo Alto, CA: Varian Medical Systems, Inc., 2023.