Accuracy assessment of Monte Carlo particle transport using jaw-interaction–based event control for multileaf collimator systems in medical linear accelerators

2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

presentation ID: 24122

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Abstract

Purpose

Monte Carlo (MC) methods are widely regarded as the gold standard for radiotherapy dose calculation; however, high computational cost can limit routine clinical application. This study evaluated two jaw-interaction–based event-control techniques in terms of absolute dose accuracy and efficiency compared with the standard analog simulation technique (SAST).

Methods

Simulations were performed with Geant4 (v11.1.1) using a TrueBeam™ (Varian Medical Systems) linear accelerator head. Two techniques were evaluated: the Jaw-Entry Termination Technique (JETT), in which particle transport is terminated upon jaw entry, and the Jaw-Interaction–filtered Transmission Technique (JITT), in which only particles traversing the jaws without interaction are transported. Across photon beam energies from 4 to 15 MV, absolute dose deviations from SAST were evaluated at the field center and directly beneath the jaws, together with simulation time. Evaluations were performed for various field sizes under fully open (40 × 40 cm²) and jaw-matched multileaf collimator configurations.

Results

For JETT, field-center absolute dose deviations were reduced when transitioning from fully open to jaw-matched configurations. In contrast, JITT maintained high accuracy, with dose deviations within 1.0% regardless of MLC configuration, field size, or photon beam energy. For both techniques, in a 10 × 10 cm² field across all energy levels, absolute dose deviations beneath the jaws outside the field were within 1.4%, and penumbra distance-to-agreement was approximately 0.1 mm at the field edge. JETT achieved a maximum speedup of 80-fold, whereas JITT provided an approximately 5-fold reduction in simulation time.

Conclusion

The techniques demonstrated trade-offs between dosimetric accuracy and computational efficiency. JETT achieved substantial acceleration at the expense of larger dose deviations, whereas JITT preserved SAST-level accuracy with meaningful speedup. Jaw-interaction–based event control offers a framework for accelerating MC dose calculations and may be suitable for clinical applications depending on accuracy requirements.

Introduction

Monte Carlo (MC) methods are stochastic algorithms that use random sampling to simulate complex systems. MC methods are widely regarded as the gold standard for radiotherapy dose calculation. However, high computational cost can limit routine clinical application.
To address this, we evaluated new event-control techniques for various field sizes under fully open (40 × 40 cm²) and jaw-matched multileaf collimator (MLC) configurations.
The purpose of this study was to evaluate the absolute dose accuracy and computational efficiency of these new techniques across photon beam energies from 4 to 15 MV.

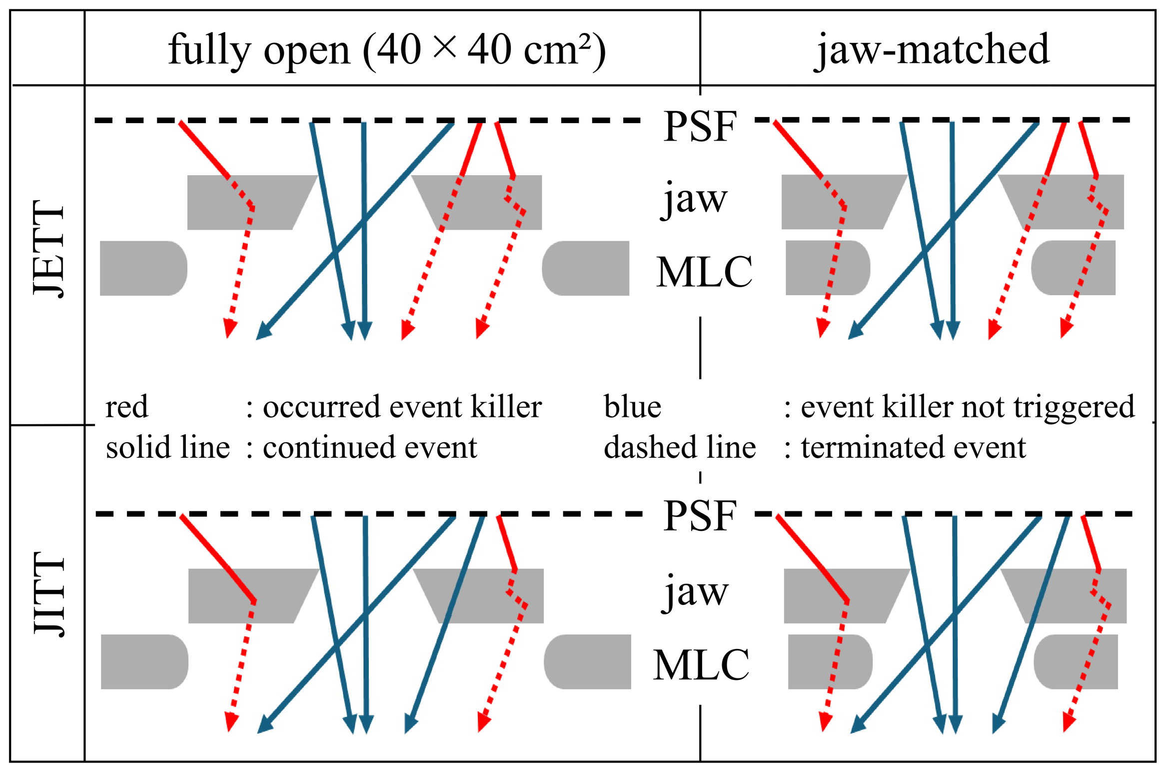
Materials and Methods

Simulating environments

- ✓ MCS tool : Geant4 version 11.1.1
- ✓ linac model : TrueBeam™ (Varian Medical Systems)
- ✓ field size : 1.0 cm × 1.0 cm, 3.0 cm × 3.0 cm, 5.0 cm × 5.0 cm, 10 cm × 10 cm
- ✓ primary photon : 4, 6, 8, 10 and 15 MV with flattening filter (WFF) : 6 and 10 MV flattening filter free (FFF)
- ✓ MLC configuration: fully open (40 × 40 cm²) and jaw-matched configurations
- ✓ primary particle : phase space file (PSF) → containing the position, momentum, and energy of particle
- ✓ physics list : G4EmStandardPhysics_option3
- ✓ MC statistical uncertainty: within 1.0%

Event-control techniques

- ✓ Jaw-Entry Termination Technique (JETT)
  - particle transport is terminated upon jaw entry
- ✓ Jaw-Interaction–filtered Transmission Technique (JITT)
  - only particles traversing the jaws without interaction are transported



Study Endpoints

- ✓ Absolute dose deviations from the standard analog simulation technique (SAST)
  - The field center, field edge and regions directly beneath the jaws
  - Absolute dose differences (%)

$$= \frac{\text{dose of JETT or JITT} - \text{dose of SAST}}{\text{field center dose of SAST}} \cdot 100$$

- ✓ Simulation time reduction compared to SAST
  - Speedup factor $= \frac{\text{simulation time of SAST}}{\text{simulation time of JETT or JITT}}$

Results and Discussion

	JETT		JITT	
	fully open	jaw-matched	fully open	jaw-matched
4 MV (WFF)	-4.63%	-0.83%	0.07%	-0.01%
6 MV (FFF)	-3.50%	-1.29%	0.09%	-0.39%
6 MV (WFF)	-3.62%	-1.63%	0.88%	-0.68%
8 MV (WFF)	-4.90%	-1.85%	-0.72%	-0.66%
10 MV (FFF)	-4.25%	-1.16%	-0.23%	0.40%
10 MV (WFF)	-4.37%	-1.93%	0.00%	-0.27%
15 MV (WFF)	-4.80%	-2.31%	-0.65%	-0.24%

Table 1: Field-center absolute dose deviations relative to SAST for JETT and JITT. Results are shown for a 10 × 10 cm² field. JETT showed a noticeable reduction in deviation when changing from fully open to jaw matched, while JITT showed little to no difference between the MLC configurations.

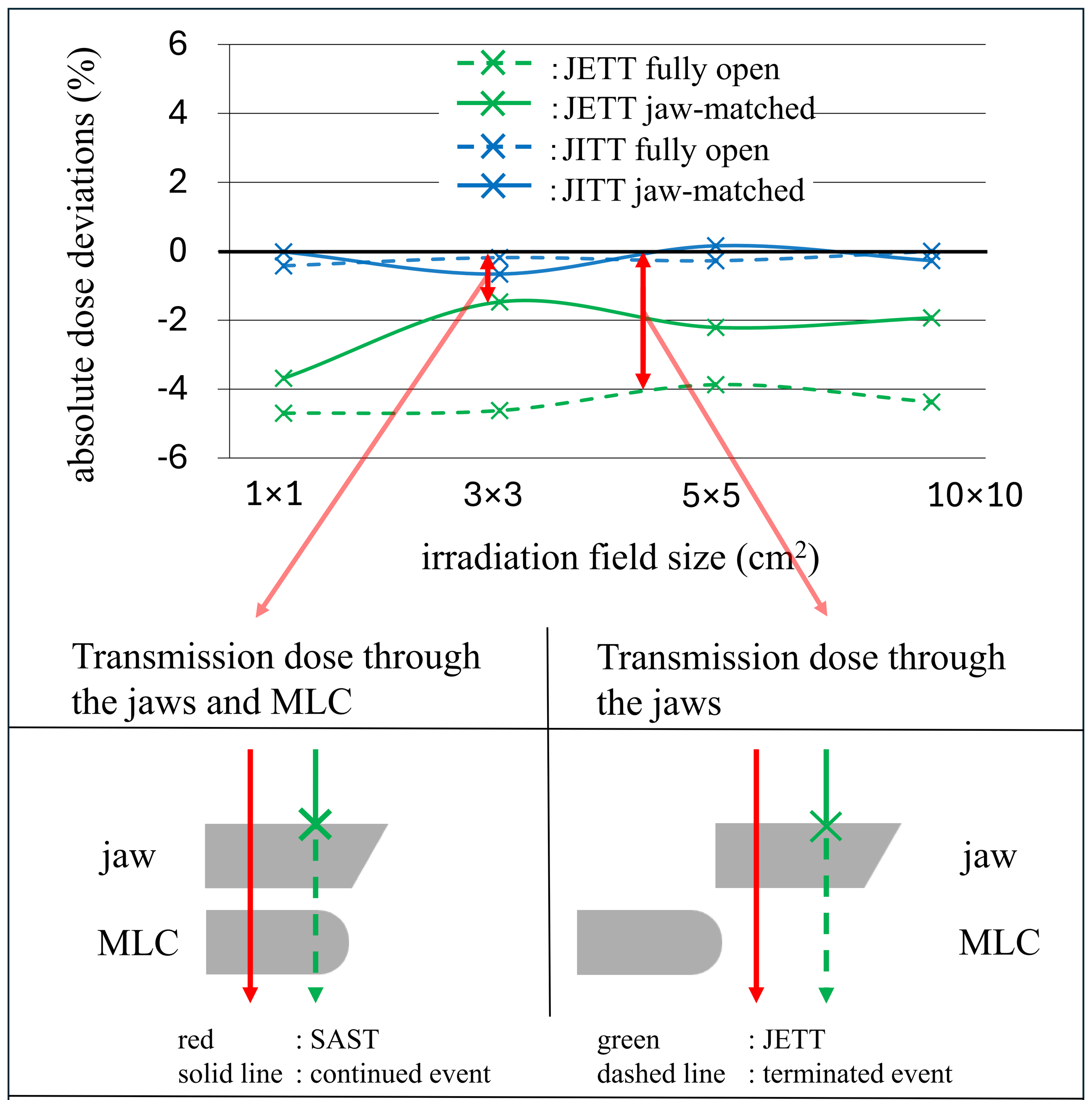


Figure 1: Field-center absolute dose deviations relative to SAST for JETT and JITT. Results are shown for a 10 MV (WFF) photon beam across all field sizes. The deviation from SAST represents the transmission dose, which is missing in JETT but correctly modeled in JITT.

	JETT		JITT	
	fully open	jaw-matched	fully open	jaw-matched
4 MV (WFF)	0.01 mm	0.08 mm	0.02 mm	0.04 mm
6 MV (FFF)	0.04 mm	0.03 mm	0.01 mm	0.01 mm
6 MV (WFF)	0.03 mm	0.05 mm	0.05 mm	0.04 mm
8 MV (WFF)	0.05 mm	0.06 mm	0.03 mm	0.01 mm
10 MV (FFF)	0.03 mm	0.06 mm	0.01 mm	0.02 mm
10 MV (WFF)	-0.03 mm	-0.08 mm	0.03 mm	-0.03 mm
15 MV (WFF)	-0.04 mm	-0.01 mm	0.01 mm	0.01 mm

Table 2: Penumbra agreement between SAST and the two event-control techniques for a 10 × 10 cm² field across all energy. Regardless of the event-control techniques and MLC configurations, the penumbra agreement was within 0.1 mm.

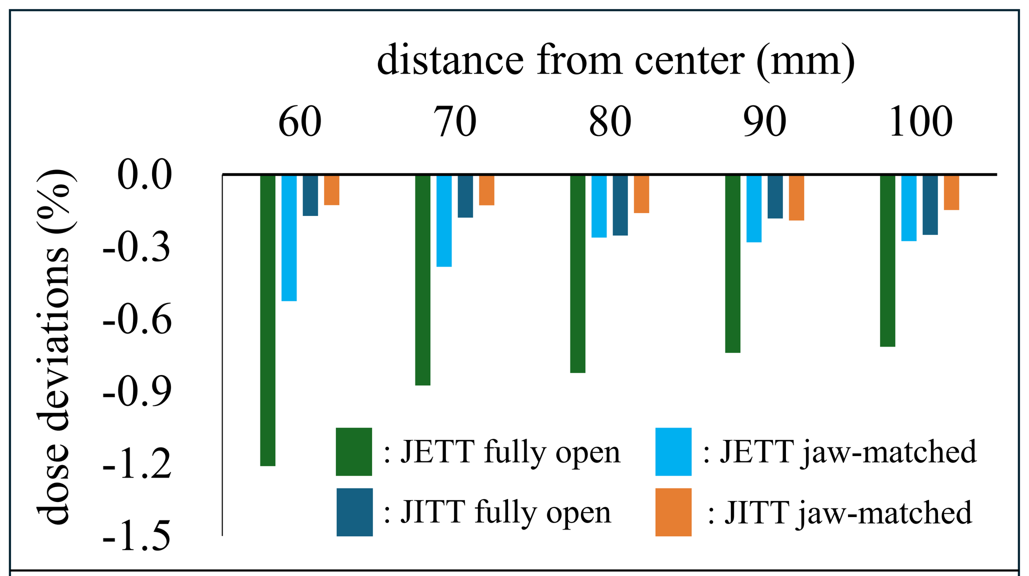
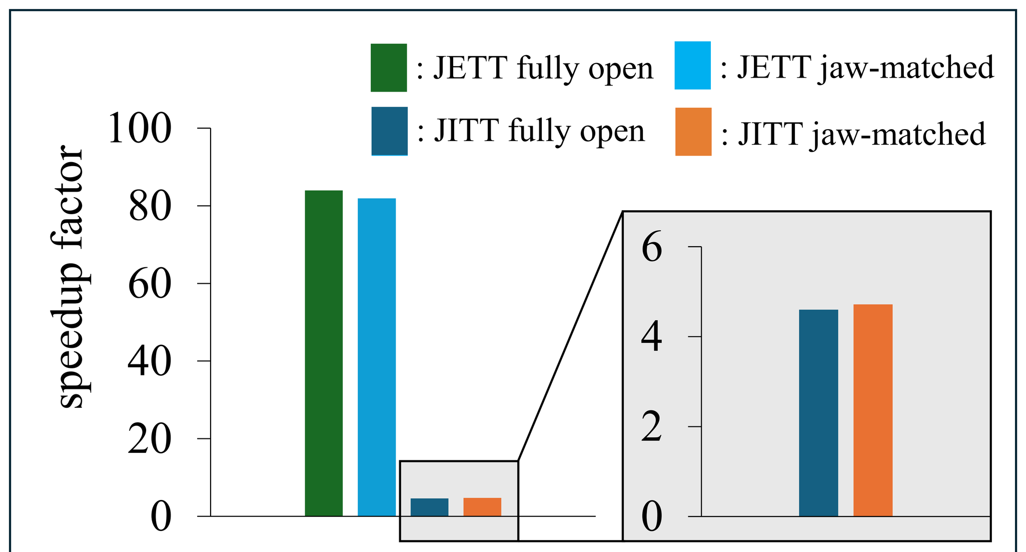


Figure 2: Absolute dose deviations beneath the jaws relative to SAST for JETT and JITT. Results are shown for a 10 × 10 cm² field at 10 MV WFF. This showed a similar trend to the field-center absolute dose deviations.



physics list	: G4EmStandardPhysics_option3 with Atomic De-excitation
atomic de-excitation	: Fluorescence X-rays and Auger electrons
field size	: 1.0 × 1.0 cm² beam energy : 15 MV (WFF)
recycle number	: The primary particles were recycled 20 times.

Figure 3: Computational efficiency expressed as speedup relative to SAST for JETT and JITT. These results indicated the conditions for maximum computational efficiency.

- JITT
  - ✓ The MLC configuration has a minimal impact on the dose distribution in the field center, penumbra and beneath the jaws.
  - ✓ This indicates that jaw-interacted particles, including scattered photons and secondary particles generated in the jaws, contributed negligibly to the evaluated dose regions under these conditions.
- JETT
  - ✓ The MLC configuration has a significant impact on the dose distribution in JETT.
  - ✓ In the jaw-matched MLC configuration, a portion of particles transmitted or scattered through the jaws is further attenuated by the MLC, thereby reducing the missing-dose component in JETT.

Conclusion

- For the JETT, the absolute dose deviation was approximately 5% with the fully open MLC but was reduced to about 2% with the jaw-matched MLC.
- For the JITT, the absolute dose deviation from the SAST was negligibly small. These results suggest that JITT may be a promising acceleration approach for MC simulations under the evaluated conditions. Further validation for patient-specific IMRT/VMAT fields is required before clinical implementation.
- JETT showed up to approximately 80-fold speedup, while JITT achieved a speedup of up to approximately 4.5 times.